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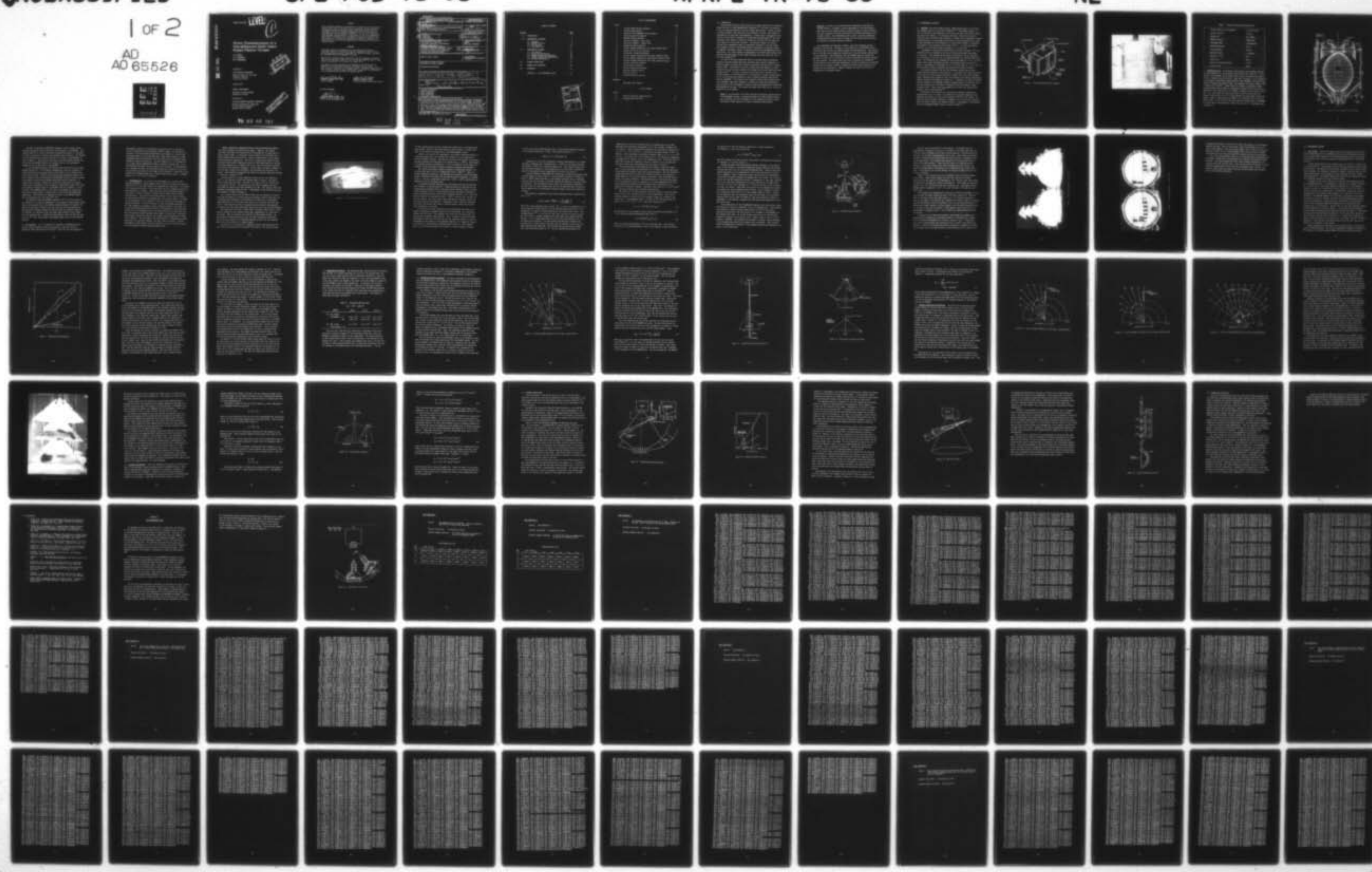

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Plume Characterization of a One-Millipound Solid Teflon Pulsed Plasma Thruster

L.C. Pless
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Prepared by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
(JPL PUBLICATION 78-96)

October 1978

Phase I Final Report

Approved for Public Release
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Prepared for:

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Edwards AFB, CA 93523

NOTICE

FOREWORD

This final report was prepared by the Jet Propulsion Laboratory, California Institute of Technology and was sponsored by the Air Force Rocket Propulsion Laboratory under MIPR No. F04611-77-X-0026, Job Order No. 305812QR through an agreement with NASA.

Work on this contract began in March 1977 and was completed in February 1978 and the pertinent studies of this period are reported herein. This report was submitted by the authors in August 1978.

This report has been reviewed by the Information Office/XOJ and is releasable to the National Technical Information Service (NTIS) At NTIS it will be available to the general public, including foreign nations. This technical report has been reviewed and is approved for publication; it is unclassified and suitable for general public.

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An evaluation was made of the pulsed plasma thruster plume-wall backscatter characteristics of the MOLSINK facility. On the thruster axis, the MOLSINK backscatter was found to be 1.23 x 10^{-2} μg-cm^{-2}-pulse^{-1}. This backscatter drops off to zero as the angle between the axis and wall location reaches 40°. This wall backscatter was found to be essentially symmetric about the plume axis. The total integrated backscatter from the MOLSINK wall is approximately equal to 5% of the total mass injected from the pulsed plasma thruster during the discharge pulse.

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1.0 INTRODUCTION

Pulsed plasma thrusters (PPT) using solid teflon propellant are inherently simple and have a flight-demonstrated reliability,[1] and thus, are expected to be of increasing interest for future flight applications. Earlier versions of these thrusters, with only tens of micropounds of thrust, were limited to drag make-up and east-west stationkeeping. A higher power, millipound thrust, version of this device, suitable for north-south stationkeeping,[2] has been developed, with roughly 20 times the propellant flow rate and 100 times the total impulse of the earlier versions. The exhaust plume of the smaller thruster has a negligible effect on spacecraft surfaces,[3] but the larger, more energetic plume of the scaled-up PPT is potentially of greater concern. In addition, the plume's effect on sensitive spacecraft instrumentation may be significant. For these reasons, investigations of the PPT plume structure and backflow characteristics of this larger thruster have been under way since it was first assembled.[4]

In order to directly assess the effect of the PPT plume on spacecraft surfaces, previous studies have been conducted using various diagnostics to directly measure the plume flux towards a spacecraft upstream of the thruster exhaust plane. Unfortunately, accurate results have been masked by a back-scattered flux of particles reflected and eroded from the test facility vacuum chamber walls.[4] In order to minimize this effect and to develop a more accurate measure of the plume-spacecraft interaction, a study is being carried out at the Jet Propulsion Laboratory using a special Molecular Sink Vacuum Facility (MOLSINK). This facility has a gaseous helium cooled anechoic-type liner (MOLTRAP) especially designed to minimize any plume-wall backscatter, thus providing a PPT environment in which accurate plume-spacecraft interaction measurements may be made. The current PPT plume study under way at JPL may be separated into two phases:

> Phase I: An evaluation of the PPT plume-wall backscatter characteristics of the MOLSINK facility, a conceptual design for a PPT backflow measurement technique, and the development of a low temperature quartz crystal microbalance (QCM) design to be used in measuring this backflow.

Phase II: A study of the plume-spacecraft interaction utilizing the MOLSINK facility, including a direct measurement of the plume backflow mass flux into the thruster plane at various distances from the thruster axis and a measure of the PPT plume mass flux profile downstream of the thruster nozzle. This information will be used to develop preliminary scaling laws which will serve to define the net backflow mass flux onto an arbitrarily located spacecraft surface.

The experiments and analyses of Phase I have been completed and are detailed in this report. Included is a description of the MOLSINK facility as modified for use with the plasma thruster and QCM diagnostics. The development of the QCM circuit design and calibration at liquid nitrogen temperatures is also discussed. The backscatter from the MOLTRAP anechoic surface was measured in total and at two specific locations using QCM test arrays designed for this purpose. The results have been used to evaluate the backscatter characteristics of the PPT plume impacting on typical locations in the MOLSINK facility and to develop a method of measuring the PPT plume backflow in the presence of this backscatter. Phase II efforts are under way and will be documented in a subsequent report.

2.0 EXPERIMENTAL APPARATUS

2.1 THRUSTER The pulsed plasma thruster under investigation in this study was designed and built at Fairchild Republic[1,4] under AFRPL contract for use in north-south stationkeeping of satellites and other applications requiring large total impulse. The operating principle, identical to previous thrusters flown on several space missions, is based on the sublimation, partial depolymerization, and subsequent acceleration of teflon propellant by a high current discharge in close proximity to a solid teflon surface. A detailed description of this thruster can be found in Ref. 1. A brief description, pertinent to the thruster plume development, is included here.

A schematic of the pulsed plasma thruster is shown in Figure 1.[5] The discharge cavity is bounded on the top and bottom by parallel electrodes, 7.6 cm apart. The discharge cavity sides are bounded by teflon propellant fuel bars kept 0.76 cm apart by a retaining shoulder cut into the anode electrode. The propellant bar thickness set the cavity depth at 3.3 cm. The discharge cavity faces downstream through a rectangular nozzle (not shown in Figure 1) extending at a half-angle of 15° to a final size of ∿ 11.5 x 16.5 cm. Some pertinent thruster operating characteristics are shown in Table I.

The thruster assembly used for the described testing differs from a flight-qualified thruster in two respects: 1) the more costly helical coiled teflon fuel rods were replaced with short straight fuel rods, and 2) commercially available mylar capacitors were used instead of the special high-energy density capacitors developed for flight use. In addition, in order to relieve the heat loading on the MOLSINK cryogenic pumping system, the thruster pulse rate was dropped from 6 sec/pulse to between 20 and 40 sec/pulse, unless otherwise noted. These repetition changes do not effect the thruster discharge or plume characteristics.[4]

The thruster was enclosed in an electrically isolated aluminum box, approximately 0.4 m on a side. To prevent the oil-filled capacitors from freezing, the interior of this box was heated to 20-26°C at all times. To check for proper thruster operation, a Rogowski coil on one of the capacitor leads was used to monitor the thruster current. A photograph of the thruster with its rectangular Mykroy nozzle is shown in Figure 2.

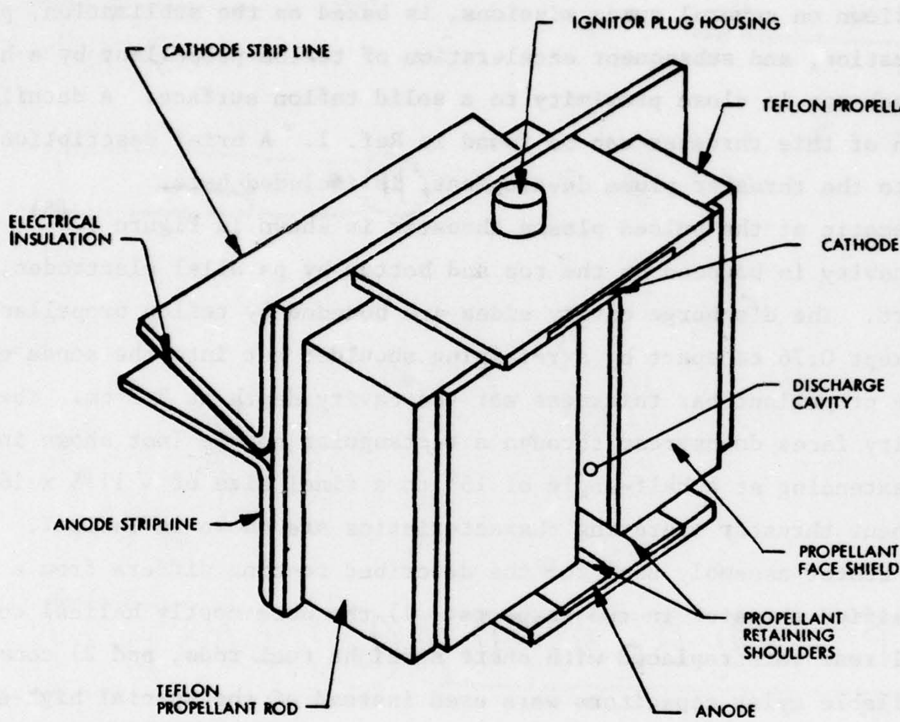

Figure 1. Pulsed Plasma Thruster Schematic

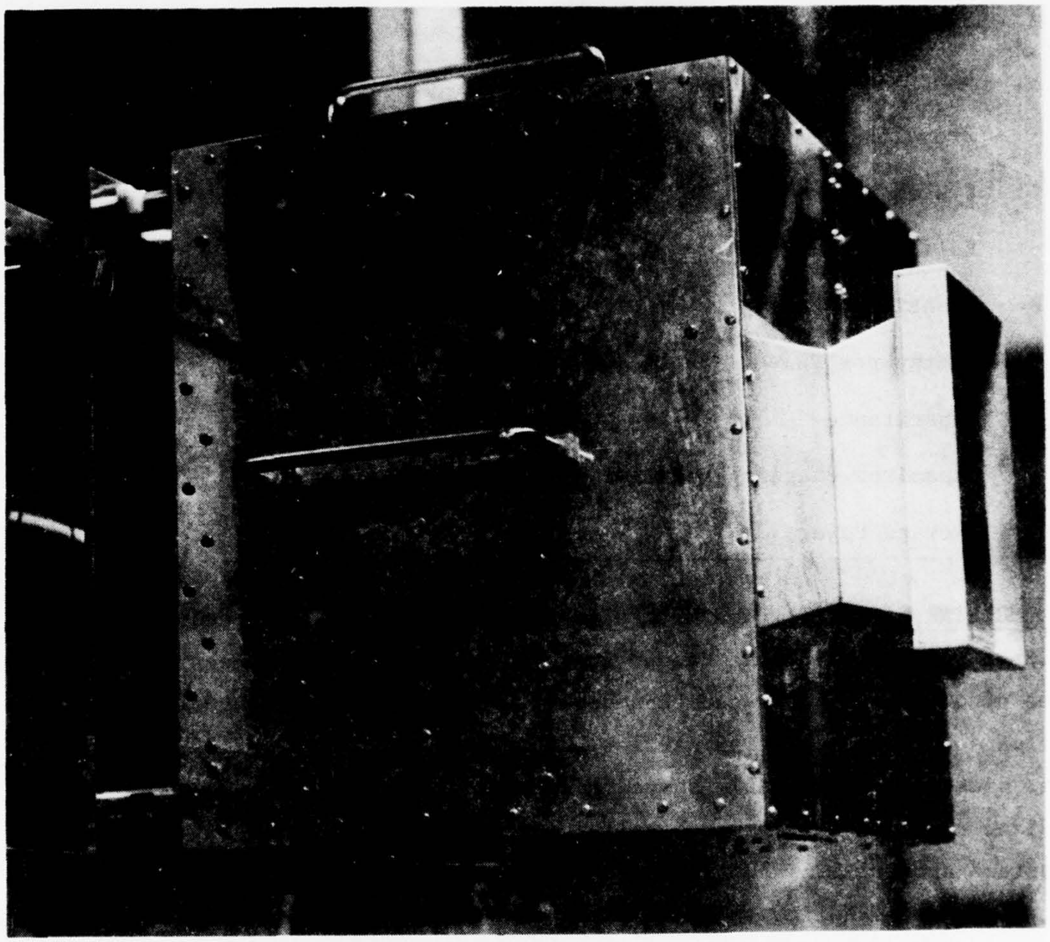

Figure 2. Pulsed Plasma Thruster

TABLE I. Thruster Operating Characteristics

Average Thrust (at 6 sec/pulse)	4.44 mN (1 mlb)
Specific Impulse	1750 sec
Impulse bit	26.5 mN-sec
Exhaust Velocity	17000 m/sec
Propellant Mass	1.56 mg/pulse
System Efficiency	26.1%
Pulse Duration	45 μsec
Repetition Rate	6 sec/pulse
Energy per Pulse	691 J
Capacitance	240 μf
Capacitor Charging Voltage	2.4 kV
Average Power	145 W

2.2 MOLSINK FACILITY The Molecular Sink Facility was designed to provide an ideal simulation of the vacuum and cold sink of outer space.(6) It consists of an ultra-high vacuum chamber with a liquid nitrogen cooled liner to provide a thermal isolation barrier. This liner encloses a 2.75 m (effective outer diameter) spherically shaped Molecular Trap (MOLTRAP), which has black anodized aluminum wedge-shaped walls, and resembles an anechoic chamber with a surface area of 186 m^2. These walls are cooled by a manifold of tubes carrying gaseous Helium (gHe) at a temperature between 10 and 15K and thus, represent a very large surface for cryogenic pumping of gases produced by the PPT. This large anechoic collecting surface is particularly useful for thruster plume studies, due to its high pumping rate and minimal backscatter. Figure 3 shows a cross-sectional schematic of the MOLSINK facility with the PPT in place. As can be seen, the actual enclosed volume within the MOLTRAP is shaped like an ellipsoid with a major axis of about 2.5 m and minor axis of about 2 m.

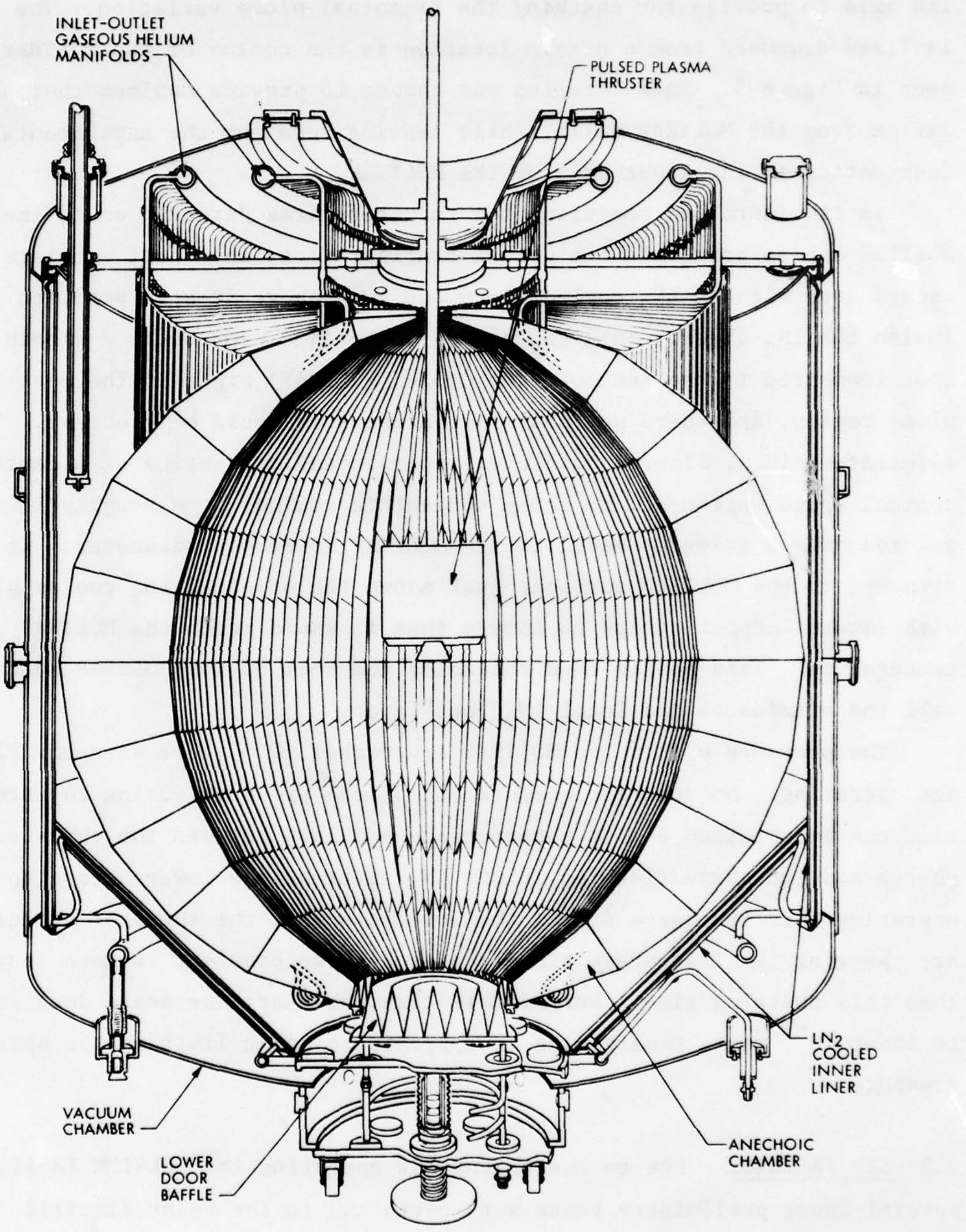

Figure 3. Molecular Sink (MOLSINK) Vacuum Chamber

The PPT is installed in MOLSINK by hanging it from a support shaft reaching through the upper access port and an opening in the MOLTRAP. This support shaft may be rotated externally allowing the thruster to turn about its axis to provide for checking the azimuthal plume variation. The thruster is fired downward from a nozzle location in the center of the MOLTRAP, as seen in Figure 3. This location was chosen to provide maximum thermal isolation from the MOLTRAP walls, while leaving room for the experimental diagnostics in the lower half of the MOLTRAP.

In its installed position, the thruster fires directly on to the lower MOLTRAP access port. In its normal configuration, this port consists of a vacuum door with an LN_2 cooled plate set just above it at a position just inside the LN_2 liner. This LN_2 cooled plate thus represents a smooth "hot" spot (compared to the anechoic gHe cooled MOLTRAP) right in the most intense plume region, and where any possible backscatter would be greatest. To eliminate this problem, a baffle was constructed consisting of a central conical spire surrounded by three concentric conical fins roughly 15 cm deep and reaching a diameter equal to the MOLTRAP lower port diameter. It was attached to the MOLTRAP surface, just above the original LN_2 cooled plate, with several copper straps to ensure that it would reach the MOLTRAP gHe temperature. This baffle thus resembles the rest of the MOLTRAP anechoic wall and eliminates the local LN_2 "hot" spot.

The pressure within the MOLTRAP approaches 10^{-12} torr when the PPT is not operating. No accurate measurement of the pressure during thruster operation can be obtained due to interference problems between the thruster discharge and ion gauge (located in the LN_2 liner at the lower access port). Operating this ion gauge during the off-cycle when the thruster capacitors are charging is inaccurate since the gauge time constant is much longer than this charging time. During this time, however, the scale does get down to about 10^{-9} torr, thus giving an approximate upper limit on the operating pressure.

2.3 SEP FACILITY Due to the expense of operating the MOLSINK facility, several short preliminary tests were performed in the Solar Electric Propulsion (SEP) high-vacuum test facility. This facility was designed for

performance testing of ion bombardment thrusters as part of the Solar Electric Propulsion System Technology (SEPST) program. The SEP facility consists of two interconnected high-vacuum test chambers, a console type monitoring station, low voltage and high voltage power supplies, an IDAC (integrated data acquisition and control) system and the necessary support systems to operate the facility. The main chamber is a 2.3 m diameter by 4.6 m long, partial hemispherical-ended, cylindrical vacuum tank. It is horizontally positioned for easy removal of the one end. All instrumentation, cabling, and power pass through bulkhead-type connectors to the test article which is attached to the chamber end by adapters. Evacuation is provided by oil diffusion pumps and a liquid-nitrogen-cooled liner. A chamber pressure of 1×10^{-6} torr is possible.

2.4 INSTRUMENTATION As a part of the development of a series of PPT diagnostic methods, a double Langmuir probe, similar to a model developed at Fairchild[4] for the same purpose, was designed and constructed. It consists of two tungsten electrodes, 1.0 cm long and 0.152 cm in diameter, parallel to each other and 0.5 cm apart. These electrodes were biased with respect to each other at various voltages to measure the PPT plume current-voltage characteristics. The shape of this characteristic can be used to estimate the plume plasma densities and temperatures at the probe location. Included in this design was a 1.9 cm diameter 6 turn coil electrode surrounding the sensing electrodes. This coil was used to clean the sensing electrodes of PPT plume deposits by setting up a glow discharge between it and these electrodes and bombarding them with electrons. The operation of this probe was checked out in a preliminary test in the SEP facility with a LES-9 type PPT. The time-resolved current wave shape was similar to that found at Fairchild under similar conditions, however, the average current magnitude was significantly smaller. This discrepancy can be attributed to differences in probe construction or operation, however, the exact cause is unknown. Further development of this Langmuir probe was postponed, until its use was required in the millipound PPT plume characterization study.

Doublet temperature compensated Quartz Crystal Microbalances (QCM's) were used to measure the mass from the plume. Briefly, two crystal controlled oscillators are formed with two electrodes on the same side of a natural quartz blank. An electronic circuit extracts the difference frequency between these two oscillators, which is proportional to the relative electrode mass and temperature. The use of a common quartz blank for both oscillators and careful temperature control of this blank keeps the relative electrode temperature at a minimal value, thus, only the relative electrode mass effects the difference frequency. In use, mass is allowed to deposit on one electrode, slowing its oscillation, and increasing the difference frequency. This frequency is measured and related to the mass deposition through a calibration constant.[7,8,9]

Because there was no known commercial source for the low temperature QCM's, it was decided to build the necessary QCM's in house. Two quartz crystal types have been used: one with a cut angle of 39^{o} 49' and one with a cut angle of 40^{o} 28'. The crystals all have 0.95 cm diameter platinum electrodes and operate at a basic frequency of 5 MHz. The crystal cover used provided an acceptance angle of 114°. A photograph of this QCM with the cover plate removed is shown in Figure 4.

Due to some concern that the QCM circuitry was too sensitive to survive the noisy environment of a teflon thruster discharge, several tests were run to determine the reliability of QCM operation in this type of environment. These tests were run in the SEP vacuum facility and utilized the LES-9 type of PPT. This thruster was used to generate typical thruster environmental conditions until the larger millipound thruster arrived from Fairchild-Republic.

The first unit built used a field effect transistor (FET) circuit. This QCM was installed on the thruster plume edge, approximately 0.5 meter from the nozzle. When the thruster was started, the QCM stopped working. An investigation revealed that one of the oscillator transistors had failed. The circuit was repaired, the shielding reworked and the test was repeated. Again, the circuit failed in a similar manner.

The next unit to be tried was a commercial hybrid oscillator-mixer circuit, which also failed when the thruster was started. The probable causes

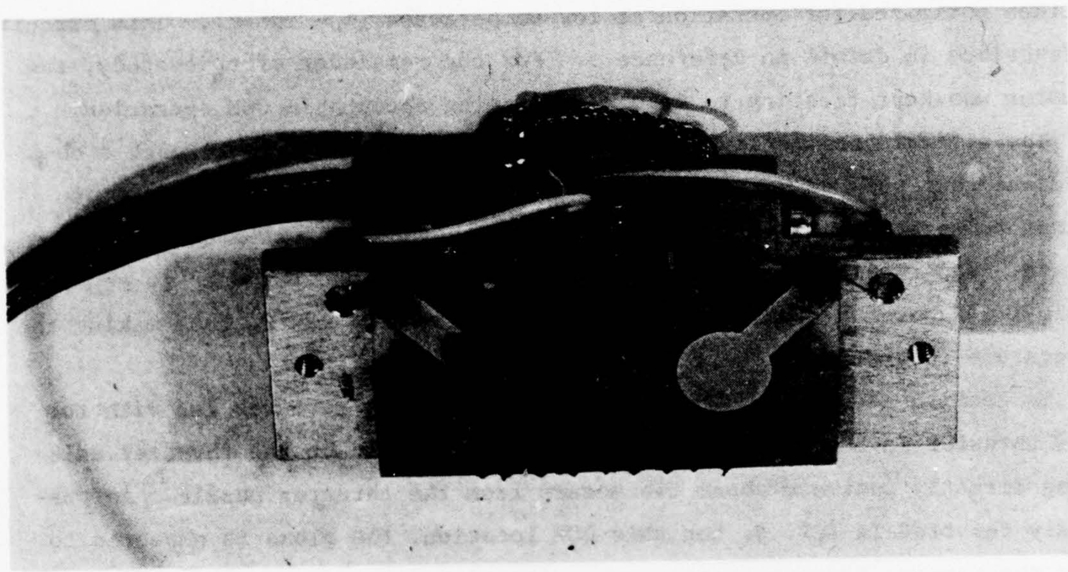

Figure 4. Quartz Crystal Microbalance

of these failures were traced to ground level shifts due to the high current pulse levels, pickup in the interconnecting coaxial leads, or induced voltages in the crystal electrodes due to the plasma magnetic field.

Finally, the circuit was redesigned to use bipolar transistors while, to eliminate ground shifts, the thruster was floated as in its operation at Fairchild Republic Company. The QCM was tested with the thruster successfully and then optimized for operation at low temperature ($\sim$ - 200°C). This circuit is described in detail in Reference 5. For the remainder of this study, the thruster was kept floating to insure continuing acceptable QCM operation.

The crystal oscillation frequency depends on temperature through a coefficient that goes to zero for temperatures round - 200°C.(7) Thus, for optimum temperature stability, the QCM should be operated at about this temperature. Experience has shown that the QCM oscillation frequency is constant within ± 1 Hz over a temperature range from - 220 to - 180°C, thus making the temperature control relatively easy.

To confirm acceptable QCM operation, one further test was run with the LES-9 thruster in the SEP facility. A QCM was mounted on the thruster axis facing directly upstream about two meters from the thruster nozzle. As previously reported in Ref. 4, for this QCM location, the plume is expected to erode the sensing electrode rather than depositing material on it. After the QCM had temperature stabilized at about - 180°C, a shutter over the QCM crystal was opened. The output signal then confirmed the expected erosion and verified the proper QCM operation. Immediately after a definite indication of erosion, the shutter was closed to prevent further erosion and a subsequent degradation of the QCM.

To relate the net mass deposition on the QCM sensing electrode to the change in difference frequency between the two electrodes, the calibration constant must be known. This constant can be derived from theoretical considerations or measured experimentally. Ref. 7 derives an equation between the deposition mass per unit area, ΔM, and the frequency change, Δf, that is independent of the density of the deposited material, $\Delta M = K\rho_g N\Delta f/F_c^{\,2}$ where K is a measure of the deposition uniformity and is equal to 1 for a smooth layer, ρ_g is the quartz density (2.65 g/cm^3), N is the frequency constant

of an AT cut crystal (1670 kHz mm) and F_c is the nominal operating frequency of the crystal oscillators (5 MHz). This equation reduces to:

$$\Delta M/\Delta f = 1.77 \times 10^{-8} \text{ g/cm}^2\text{-Hz} \quad (1)$$

Initially, to check this calibration constant experimentally, an attempt was made to deposit argon (freezing point = - 189°C) on the liquid nitrogen cooled QCM ($\sim$ -200°C) at a controlled known rate. This attempt failed since the argon vapor pressure at this temperature is so large that a significant amount of the deposited mass revaporized and obscured the results.

A second attempt at experimentally calibrating the QCM was performed using a method similar to that of Ref. 8. This procedure consists of cooling the QCM to - 200°C, depositing water on the sensing electrode until a reasonable layer is built up, and then, in vacuum, heating the QCM until the water begins to evaporate. This evaporation rate is known via an analytical expression derived in Ref. 8, thus the mass loss rate off the QCM electrode is known and can be compared with the difference frequency change to give the calibration constant.

The analytical expression for the water evaporation rate, corrected from Ref. 8, is:

$$\ln \Delta\dot{M} = 30.888 - \frac{6091.4}{T} + \ln\left[\frac{1}{C}\sqrt{\frac{M}{2\pi RT}}\right] \quad (2)$$

where $\Delta\dot{M}$ is the evaporation rate in g/cm^2-sec, T is the ice temperature, M is the ice molecular weight (18 g), R is the universal gas constant (8.3×10^7 erg/gm-mole - K) and C is the Clausing factor for the QCM cover plate. This Clausing factor [10] is the ratio of water vapor escaping through and around the cover plate to vacuum, divided by the total vapor flux leaving the QCM surface. It is a complicated function of the cover plate geometry, and is not known very accurately. For this reason, the QCM being calibrated was equipped with a spring-loaded cover that could be removed, in situ, once the water deposition was completed. This insured that the effective Clausing factor was identically equal to 1.0. For the calibration procedure, the

temperature for the ice on the QCM crystal is assumed equal to the QCM mounting block temperature maintained at 153 ± 5K, through a feedback control system. Thus, the theoretical QCM mass flow rate given by equation (2) is $1.99 \pm 1.5 \times 10^{-9}$ g/cm^2 -sec. The measured frequency change is 102 ± 13 Hz/hour, so the experimental calibration constant ($\Delta M/\Delta f$) is $7.0 \pm 6.5 \times 10^{-8}$ g/cm^2 Hz. The large error bar is primarily due to the exponential dependence on temperature of equation (2) for the evaporation rate. This final value of $\Delta M/\Delta f$ does include the theoretical value of equation (1) in the error bar and thus provides some confirmation that this value is correct.

While researching the QCM calibration procedure, a paper was found (Ref. 9) which describes the calibration of a virtually identical QCM using vacuum sputtered aluminum rather than evaporating water. The only difference in QCM construction was in the use of conductive epoxy at JPL instead of indium solder for the crystal mounting connections. This difference has no effect on the QCM calibration. The measured data in this paper were within 2% of the theoretical value of equation (1) and when combined with the previous calibration procedure provide satisfactory confirmation of the theoretical calibration constant. Therefore, this value of 1.77×10^{-8} g/cm^{-2} Hz^{-1} was used throughout the following investigations.

The ability of the QCM to measure small mass fluxes is directly proportional to the total operating time for a given measurement. The rate of frequency change is given by the net frequency change, Δf, divided by the total time, T. The measured flux, S, is equal to the QCM calibration constant, (1.77×10^{-8} g/cm^{-2} - Hz^{-1}) times this frequency rate:

$$S = 1.77 \times 10^{-8} \frac{\Delta f}{T} \text{ g/cm}^{-2}\text{-sec}^{-1} \quad (3)$$

The resolution of the frequency counter limits the smallest measurable Δf to ± 1 Hz, thus the smallest measureable mass flux is:

$$S = \frac{1.77 \times 10^{-8}}{T} \text{ g/cm}^{-2}\text{-sec}^{-1} \quad (4)$$

which is inversely proportional to the net operating time. The effective resolution of the QCM measurement is due to the frequency counter resolution

of equation (4), and the frequency changes due to random temperature fluctuations (± 1 Hz), and is given by:

$$\pm \Delta S = \frac{3.54 \times 10^{-8}}{T} \text{ g/cm}^{-2}\text{-sec}^{-1} \qquad (5)$$

The error induced from other sources, such as time or calibration inaccuracies, is negligible for normal values of T.

Having developed a QCM design which operates acceptably at low temperatures in the presence of the PPT discharge and having calibrated this design, 20 units were built for the following PPT-MOLSINK tests. These 20 units were tested individually at LN_2 temperatures, and 17 were selected for installation in MOLSINK. These 17 QCM's were found, when tested at LN_2 temperature, to have base difference frequencies ranging from ∿2 to 20 kHz. As a check to insure that the QCM calibration constant is independent of this base frequency and of the other small differences in the QCM construction, two QCM's were selected, one with a base frequency of 1.75 kHz and one with a base frequency of 19 kHz, and tested. These QCM's were placed as close together as possible and exposed to a vacuum evaporated water source. The two changes in difference frequencies were within 1 Hz of the average change of 106 Hz. Because the net deposited mass was essentially equal for both QCM's, the calibration constants must also be equal to within 1%, thus the calibration constant is independent of the QCM base frequency and other associated differences in the QCM construction.

Local measurements of the PPT-MOLSINK backscatter were made using several QCM's mounted in molecular "skimmers" tied to the MOLTRAP wall. These skimmers were designed to isolate (skim) a small portion of the PPT plume and to examine the backscatter from this portion as it impinges on the MOLTRAP wall. Two skimmers were used: one on the thruster axis and one at the PPT plume boundary 40 degrees off the thruster axis. Figure 5 shows a view of the two skimmers in MOLSINK. The skimmers were designed to provide a well-collimated 2.54 cm diameter beam which would interact with the MOLTRAP. QCM's mounted inside the hemispherical portions of the skimmers measured the backscatter as a result of this interaction.

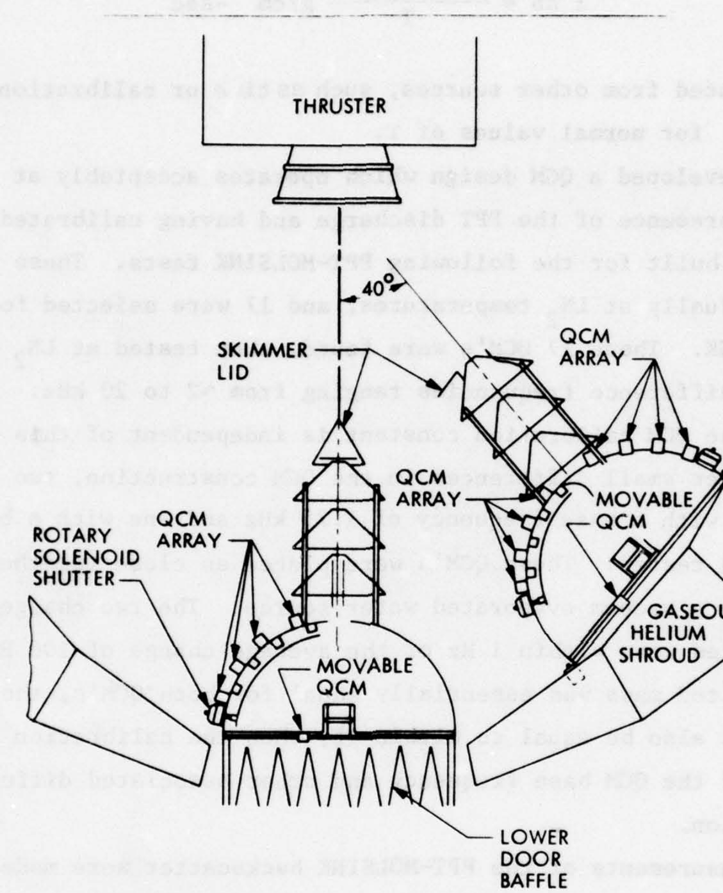

Figure 5. MOLSINK Skimmer Assembly

Figure 6 shows a photograph of the skimmers. The skimmer with the perpendicular collimator is for use in the center of the beam, while the one with the tilted collimator is for the off-axis position. Various electronics boxes for the internal instrumentation can be seen. These boxes are mounted on teflon thermal isolators and heated with strip heaters to acceptable operating temperatures. The skimmers were equipped with spring-loaded lids to control the plume entrance. These lids were opened by supplying an overcurrent to fuse wires holding them closed, causing the wires to melt, and allowing springs (made of molybdenum for low temperature use) to pull them open. The spring for the on-axis skimmer can be seen in Figure 6 at the top of the collimator.

Figure 7 is an internal view of the skimmers, with the on-axis skimmer on the right. This on-axis skimmer has only four QCMs since any mass reflected from the center of the axisymmetric door reflector that this skimmer is mounted on is expected to also be axisymmetric. These QCMs are mounted at angles of 8°, 23°, 38° and 53° from the collimator axis. The eight off-axis skimmer QCMs are mounted at $\pm 6^{\circ}$, $\pm 22^{\circ}$, and $\pm 36^{\circ}$ and $\pm 51^{\circ}$ from the collimator axis.

Both skimmers were equipped with rotating plate shutters designed to control the QCM view angle between the usual 114° down to about 42°. This was done by rotating a plate with small holes in it to a position directly in front of the QCM's. The shutters were installed to provide a means of decreasing the QCM deposition rate if necessary, since once the deposition mass on a QCM sensing crystal reaches a critical amount, the difference frequency drops to zero and no data can be obtained. These shutters can be seen in each of the skimmers in Figures 5 and 7. As it turned out, these QCM shutters were not needed.

In addition to the previous equipment, each skimmer was supplied with a movable QCM and stepper motor mechanism mounted on a parallel rail arrangement just above the MOLTRAP wall, as seen in Figures 5 and 7. These QCM's were used to sweep through the collimator beam to provide a flat reflecting surface to verify that the beam was getting through the collimator by increasing the mass flux to the QCM's mounted on the hemisphere, and to monitor the

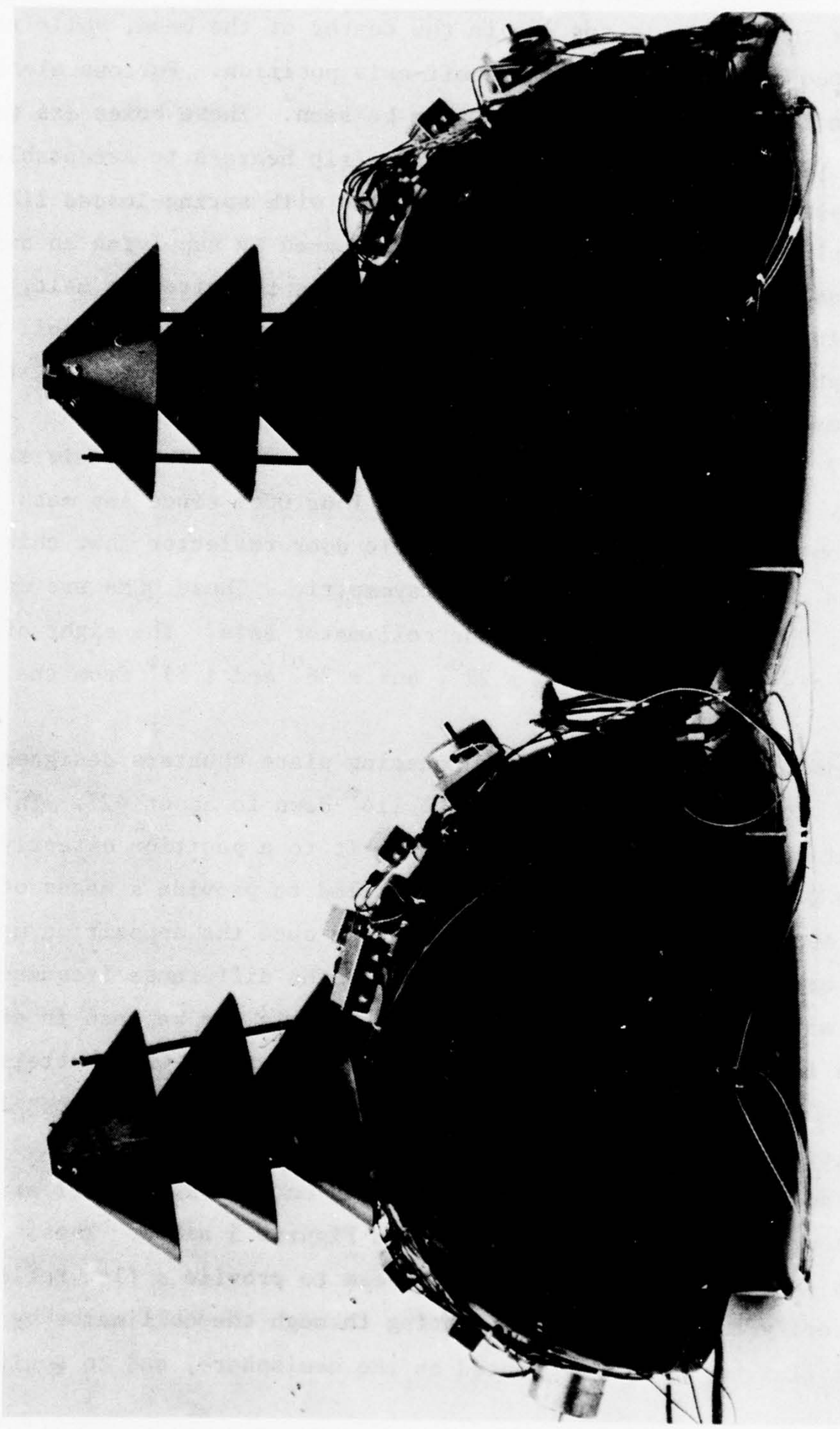

Figure 6. Molecular Skimmers - Outer View

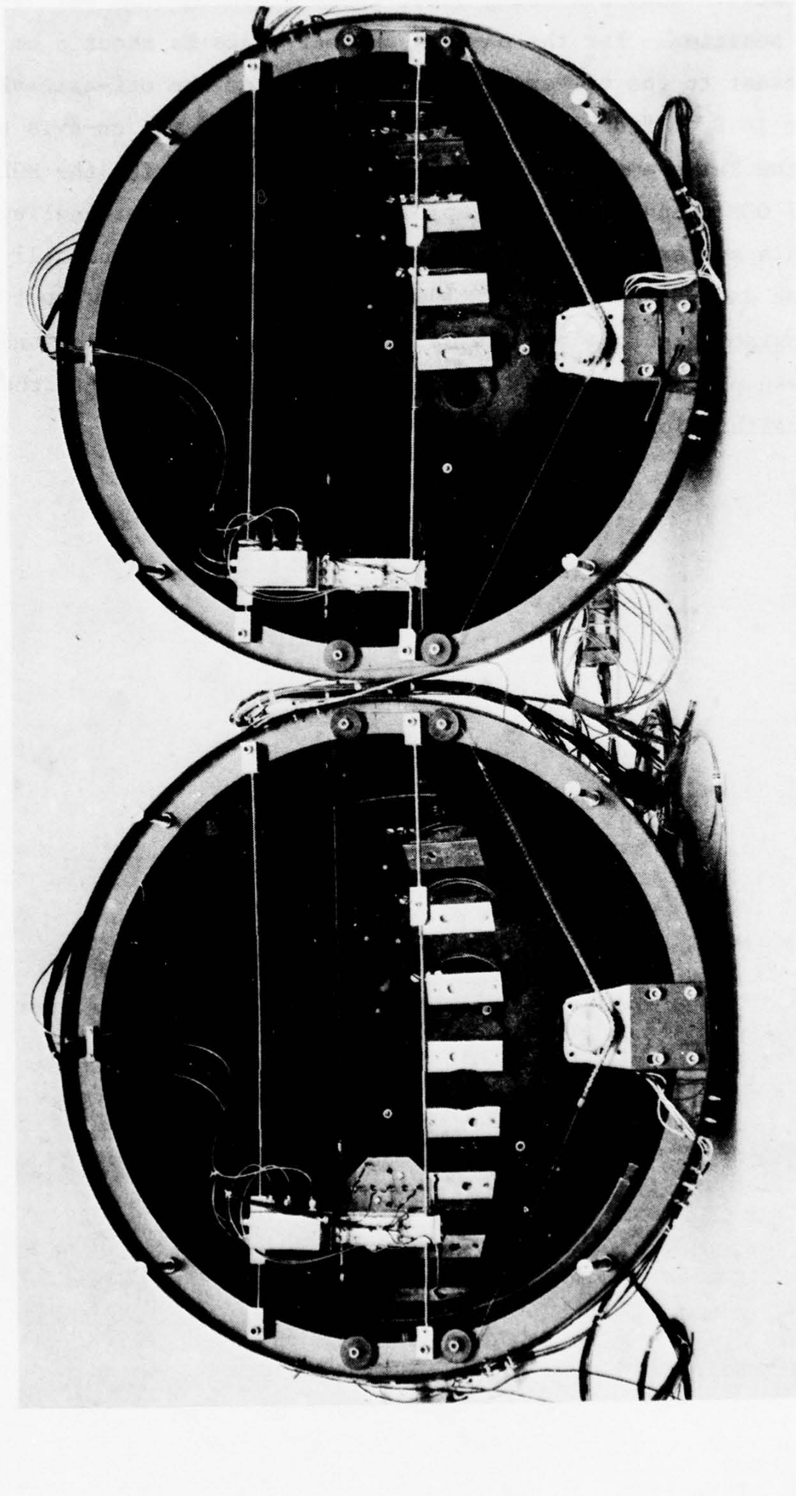

Figure 7. Molecular Skimmers - Inside View

collimated beam shape by observing the movable QCM signal as the QCM sweeps through this beam. When not being used, these scanning QCMs were set in their parked position. For the on-axis skimmer, this is about 8 cm from the side-wall closest to the off-axis skimmer, while for the off-axis skimmer this position is 8 cm from the side-wall furthest from the on-axis skimmer.

Due to the large amounts of data to be collected during the MOLSINK test (including 17 QCM's and 21 thermocouples) an automatic data handling system was used. This system sampled the data output channels periodically and recorded these data on paper tape. This tape was used as the input of a data reduction program which plotted the data in graphical form. The best fit slopes of these plots were used to find the net mass fluxes into the QCM's via the QCM calibration constant.

3.0 EXPERIMENTAL PROGRAM

3.1 <u>TEST HISTORY</u> Before the primary testing to determine the actual backscatter characteristics of the MOLTRAP walls, several preliminary tests were run to insure proper operation of the millipound thruster after its arrival from Fairchild, and to check the thruster and QCM operations in the MOLSINK facility.

To check the operation of the thruster after its arrival, a test was run in the SEP facility. The thruster was installed and operated per instructions from Fairchild. The thermal control system, consisting of the resistor heated metal container, the thermistor temperature feedback controller, and the associated thermocouples, was checked for proper operation at liquid nitrogen (LN_2) temperatures. No unusual behavior was found and the thruster operation was considered acceptable for the following studies.

A second test was then carried out to check the PPT and QCM operations in the MOLSINK facility. The thruster was installed as described in section 2.2 of this report, while three QCMs were installed on a radial support bracket in a plane 51 cm behind the thruster nozzle, 38 cm, 51 cm and 64 cm from the thruster axis, respectively. The QCM radial bracket was initially perpendicular to the longer nozzle dimension i.e., parallel to the teflon feed bars. The MOLSINK chamber was cooled with LN_2 only while the thruster was fired once every 36 seconds. Both the PPT and the QCM operations were found to be acceptable. During this test, the thruster was rotated 90^o so that the three background QCMs were perpendicular to the shorter nozzle dimension and to the feed bars. This was done to check the azimuthal symmetry of the background flow from the thruster. The QCM difference frequencies plotted versus operating time for this test are shown in Figure 8. The slopes of these curves are directly proportional to the net mass flux, through the QCM calibration constant found in Section 2.4. Rather than continuing to present these rough data in the main part of this report, they are recorded in Appendix A. Only the mass flux values deduced from these data will be presented in the remainder of this report.

Having completed the preliminary testing satisfactorily, the main backscatter testing was begun. The complete experimental assembly, including the PPT thruster, the three background QCMs and the two previously described

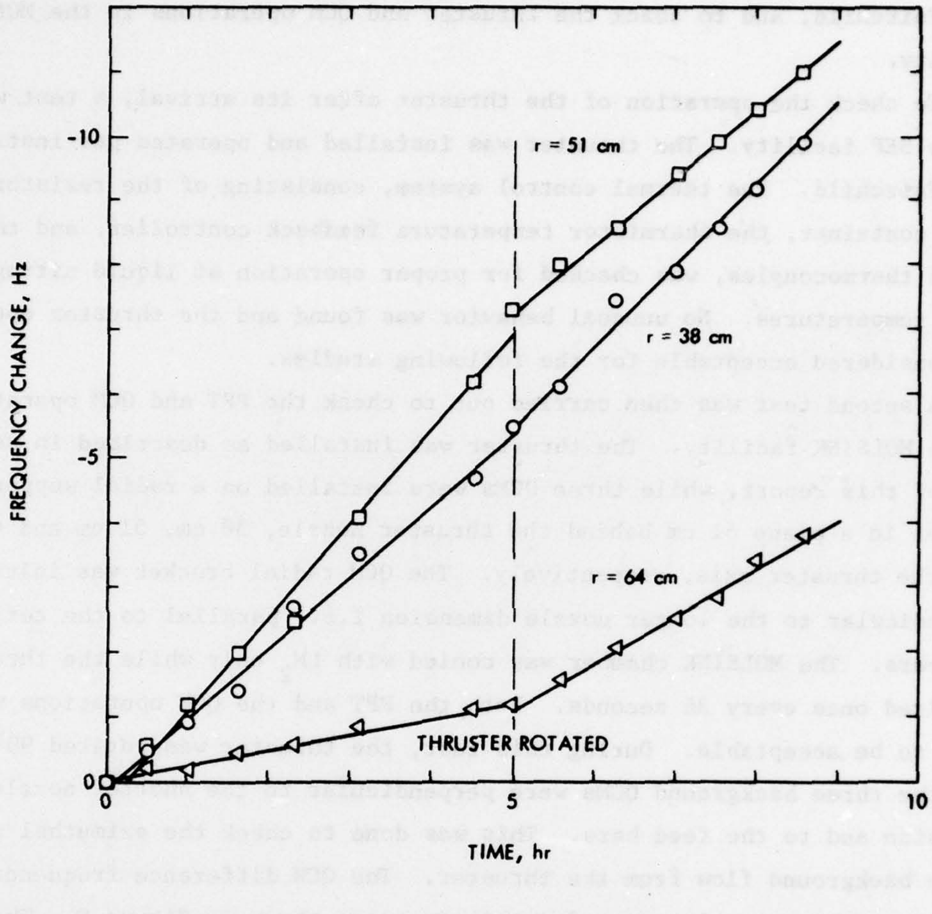

Figure 8. Background QCM Frequencies

skimmers, was installed in the MOLSINK facility. The skimmers were mounted on the inner edges of the MOLTRAP anechoic fins, one on the thruster axis and one 40^{o} away from this axis. Initially, the areas between the fins were left uncovered, allowing plume particles to enter the skimmers from around and underneath the hemispherical shields. Thus, the QCM's in the skimmers measure the wall backscatter from the 2.5 cm diameter skimmer collimator and from this edge leakage. Installation and checkout of the complete system was completed on October 21, 1977, when the pumpdown was started. Due to an initially large outgassing rate and various problems with the gaseous helium cooling system, the MOLTRAP temperature did not reach operating levels ($\sim$ 14K) until October 28. Several of the QCMs failed when the tank reached gaseous Helium temperatures, but heating their electronics assemblies started them working again.

During the first segment of this test, data were taken only from the on-axis skimmer and the three background QCMs. The scanning QCM, mounted in the on-axis skimmer at the MOLTRAP surface, was intended to measure the input profile of the collimator beam, however, the moveable platform used to hold this QCM moved on its support tracks in very abrupt jumps which lead to a rapid breakdown of the relatively fragile QCM. Despite this problem, some scanning QCM data were taken, until a clamping diode on the stepper motor shorted and burned out the control circuitry. The scanning QCM position was then unknown, so the test was stopped. The tank was warmed up and vented, the circuit repaired, several thermocouples were added to monitor critical areas, and the test was restarted on November 16, 1977.

After the thruster was started, and prior to opening the skimmer collimator lids, a continuity test on the on-axis skimmer fuse link was done which indicated an infinite resistance and an open lid. Rather than venting the tank and starting over, the test was continued in the hope that the on-axis lid was, indeed, open. Data were taken from both skimmers and the background QCMs. For part of this test segment, the PPT pulse repetition rate was changed from 36 sec/pulse to 23 sec/pulse to increase the data accumulation rate. The net deposition rates per time increased accordingly while the deposition rates per pulse remained constant. Data were taken from the skimmer's scanning QCMs in their parked positions, and no scanner movement

was attempted. This test segment was stopped on November 20, 1977. When the tank was opened, the on-axis skimmer lid was found to be closed, thus the previous data are due to the plume backscatter under the skimmer edge. The skimmer test circuit was found to have a break in an internal tank lead wire.

A skirt was added to the base of the on-axis skimmer to prevent backscatter under the skimmer edge and the test was restarted on November 28, 1977. Again, data were taken from the parked scanning QCMs as well as from the skimmer QCMs. When sufficient data of this type had been taken, the on-axis scanning QCM was moved into the collimator beam, however, before any data were available the thruster was found to be off. An investigation revealed the problem was inside the tank, so this test segment was terminated on December 2, 1977. When the thruster was removed, a coaxial adapter in the thruster charging line was found to be blown apart. The problem was repaired and the wiring system for the thruster was inspected.

For the final test segment, a skirt was added to the lower edge of the off-axis skimmer, to prevent backscatter leakage. The test was continued on January 19, 1978, but because of minor problems with the MOLTRAP cooling system, operating temperature was not reached until January 30, 1978. Data were taken from both skimmers and the scanning QCMs. The off-axis skimmer QCM signals were still outside the instrumentation resolution after several days of operations indicating that either the plume backscatter or the plume density itself is negligible. The scanning QCM was stepped into the collimator beam to measure the incoming collimated beam and to provide a smooth reflecting surface which should enhance any backscatter. Once in position the scanning QCM was found to be inoperable so no direct collimated beam measurements were possible. The skimmer QCM signals remained small, even with the smooth scanning QCM reflecting surface, thus it is concluded that the PPT plume density is negligible at this off-axis location.

On February 5, 1978 the thruster high voltage supply was found to be off. The overcurrent trip circuit had shut off the supply after its regulator had failed and may have charged the thruster capacitors to 4 kV for about 30 sec. Rather than stopping the test, the charging voltage was set manually at 2 kV (down from 2.4 kV), assuming that the mass per pulse can be scaled with the square of the voltage ratio.[11] The test was stopped when sufficient data were taken on February 6, 1978.

3.2 <u>BACKGROUND QCM RESULTS</u> The background QCM's mounted behind the thruster (See Section 3.1) provide information on the sum of the upstream mass flux from the thruster plume backflow and the plume-wall backscatter. Data were taken with these QCM's under two conditions: first, with the MOLTRAP cooled by LN_2 only, without the skimmers, and second, with the skimmers in place and with the MOLTRAP cooled to gHe temperatures. In addition, for the first condition, the thruster was rotated to check the net QCM signal symmetry. This rotation was from the usual position (0°) where the QCMs were parallel to the teflon feed bars to a position (90°) where they were perpendicular to these feed bars and on the cathode side of the thruster. The results of these tests are shown in Table II.

TABLE II. Background QCM Flux Data

($\mu g - cm^{-2} - pulse^{-1}$)

RADIUS	38 cm	51 cm	64 cm
#1) LN_2 cooled			
no skimmers - 0°	0.98×10^{-4}	1.27×10^{-4}	0.21×10^{-4}
- 90°	1.09×10^{-4}	0.92×10^{-4}	0.65×10^{-4}
#2) gHe cooled with skimmers - 0°	4.2×10^{-4}	3.15×10^{-4}	2.62×10^{-4}

The first test, with only LN_2 cooled walls, represents a worst case backscatter situation compared to the second gHe cooled test, since the MOLTRAP cryopumping is minimal at LN_2 temperatures. The large increase in the QCM fluxes between tests 1 and 2 is attributed to the presence of the skimmers for test 2. This increase thus suggests that most of the mass flux arriving at these background QCMs is due to plume-wall backscatter, as will be confirmed by the skimmer data in the following discussion. The two

thruster positions of test 1 show little differences in QCM signals indicating that the plume-wall backscatter is relatively independent of the thruster azimuthal position and, thus, is approximately azimuthally symmetric.

3.3 SKIMMER BACKSCATTER MAGNITUDE In order to estimate the net backscatter from the MOLTRAP walls, this backscatter was measured locally by the skimmers. The particular information required for this estimate is given by the results of the skirted skimmer tests, where only the backscatter from the two 2.54 cm diameter skimmer collimator beams was measured.

The results of the skirted on-axis skimmer measurement are shown as the solid line in Figure 9, where the net mass flux into the QCMs mounted on the skimmer hemisphere is plotted versus the angular location of the QCM with respect to the hemisphere center. The QCM data points at 23° and 53° are within the effective QCM resolution calculated to be 10^{-5} μg cm^{-2} $pulse^{-1}$ for this measurement. These data show a strong dependence on scattering angle as would be expected from a narrow beam reflecting off the concentric baffle arrangement on the MOLTRAP lower door. This baffle (See Section 2.2) is symmetric about the collimator-thruster axis, thus the data is also expected to be symmetric.

The off-axis skimmer data with the skirt in place was taken over a five day period with a PPT pulse rate of 36 sec/pulse. None of the off-axis QCMs ever reached a signal within the effective QCM resolution, thus the net backscatter flux is less than 10^{-6} μg cm^{-2} $pulse^{-1}$ for any QCM location within the off-axis skimmer hemisphere. As discussed in Section 3.1 this low signal is primarily due to a negligible plume density at the skimmer location 40° away from the thruster axis. Thus, the plume-wall backscatter must originate in the region where the highest density part of the plume intersects the MOLTRAP wall, i.e., in a region within 40° of the PPT axis.

From the results of these skirted skimmer tests, it is possible to estimate the net mass flux being backscattered off the MOLTRAP surface. For the on-axis skimmer, the measured flux of Figure 9, integrated over the inner hemispherical skimmer area, gives the total backscattered flux produced by the incoming collimated 2.5 cm beam. To simplify this integration and because of the relatively large error in the data of Figure 9, the flux distribution over the hemispherical surface will be assumed uniform and equal

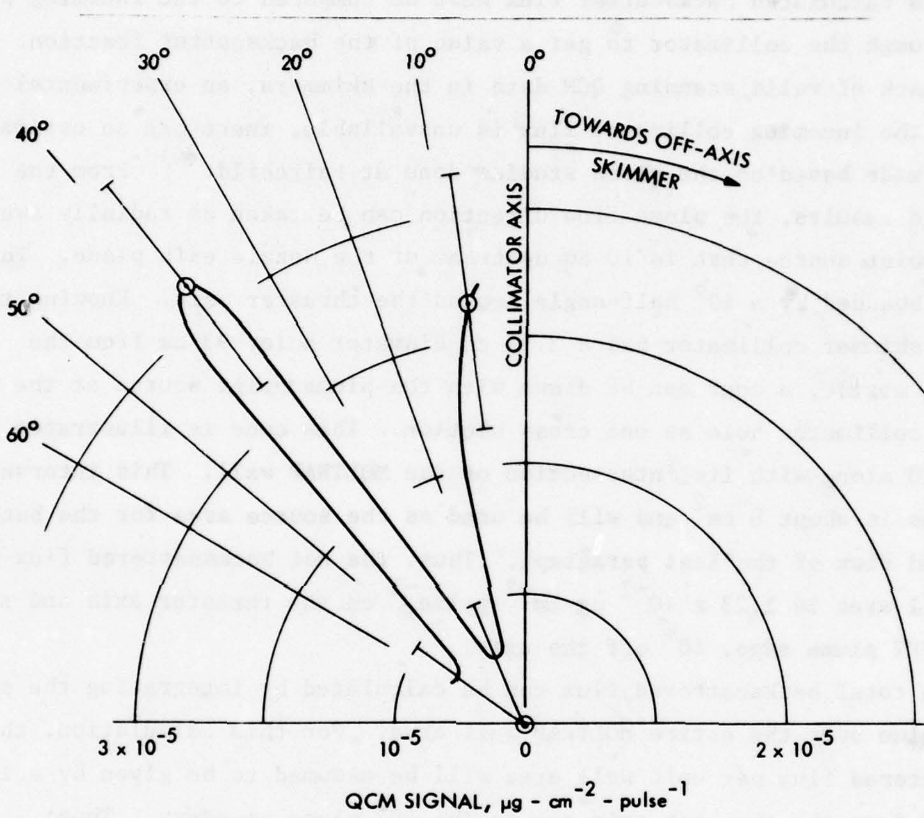

Figure 9. On-Axis Skimmer Backscatter (Lid Open, Skirted Base)

to the estimated average value of 2.5×10^{-5} μg cm^{-2}-pulse^{-1}. This assumption will result in an over-estimate of the net backscatter. For a 25 cm radius skimmer hemisphere the area is 3926 cm^2 and the total backscattered flux becomes 9.8×10^{-2} μg-pulse^{-1} for the on-axis skimmer. For the off-axis skimmer the backscattered flux is essentially zero.

This calculated backscatter flux must be compared to the incoming plume flux through the collimator to get a value of the backscatter fraction. Due to the lack of valid scanning QCM data in the skimmers, an experimental profile of the incoming collimated flux is unavailable, therefore an estimate will be made based on the plume studies done at Fairchild.[4] From the Fairchild results, the plume flow direction can be taken as radially away from a point source that is 10 cm upstream of the nozzle exit plane. This radial flow is bounded by a 40° half-angle around the thruster axis. Knowing the on-axis skimmer collimator has a 2.54 cm diameter hole, 93 cm from the thruster nozzle, a cone can be drawn with the plume point source at the apex and the collimator hole as one cross section. This cone is illustrated in Figure 10 along with its intersection of the MOLTRAP wall. This intersected wall area is about 8 cm^2 and will be used as the source area for the backscattered flux of the last paragraph. Thus, the net backscattered flux per unit wall area is 1.23×10^{-2} μg-cm^{-2}-pulse^{-1} on the thruster axis and zero at the PPT plume edge, 40° off the axis.

The total backscattered flux can be calculated by integrating the previous value over the entire MOLTRAP wall area. For this calculation, the backscattered flux per unit wall area will be assumed to be given by a linear drop-off from the thruster axis out to the 40° plume boundary. Thus:

$$\dot{m}_{SA} = 1.23 \times 10^{-2} \left[1 - \frac{\theta}{0.628}\right] \qquad (6)$$

where $\dot{m}_{SA}$ is the local value of the backscatter flux per unit wall area (μg-cm^{-2}-pulse^{-1}), θ is the angle (in radians) measured from the thruster axis and the constant number, 0.628 is 40 degrees in radians. This linear function is shown in Figure 11 along with the measured data and a schematic of the integration over the MOLTRAP wall. For this integration, the MOLTRAP

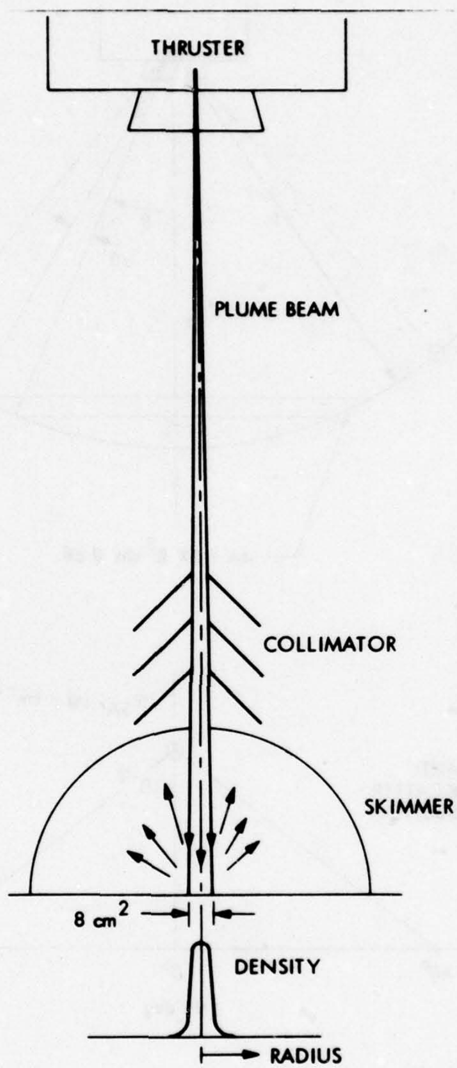

Figure 10. Backscatter Source Distribution

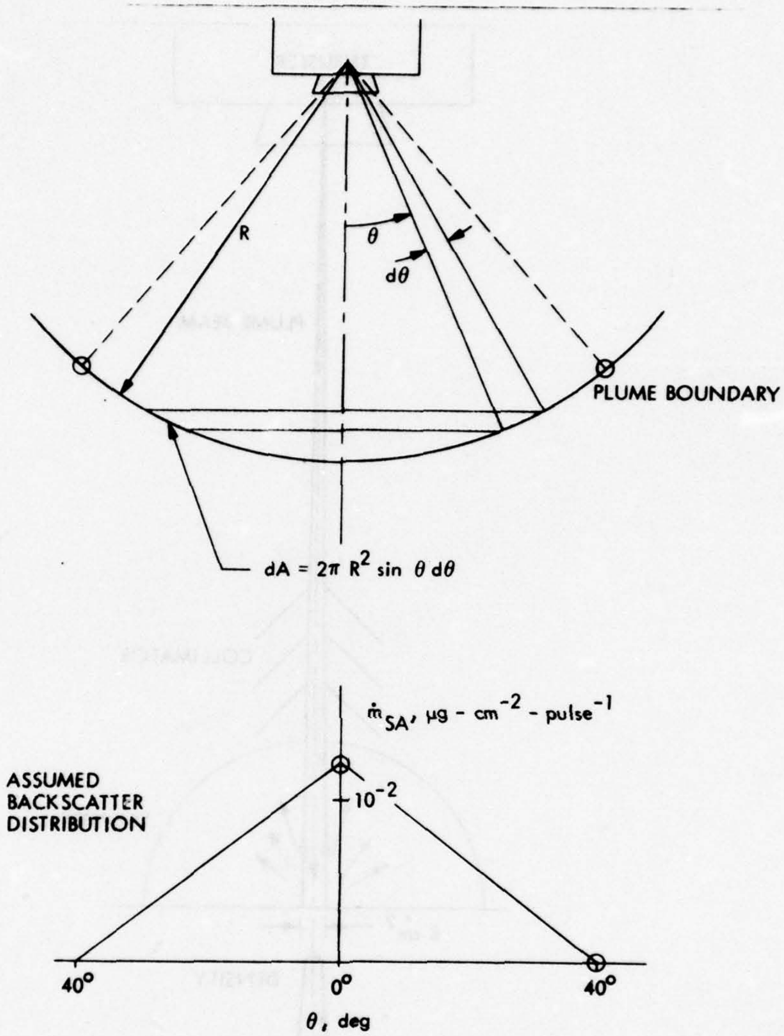

Figure 11. Backscatter Integration Method

surface can be taken as spherical, with a center at the thruster plume origin and a radius of 120 cm. A differential area element is also shown in Figure 11. Integrating Equation (6) over this area gives:

$$\dot{M}_S = \int_{0°}^{40°} \dot{m}_{SA} \; 2\pi R^2 \sin\Theta \, d\Theta$$
$$= 88.4 \;\; \mu\text{g-pulse}^{-1} \qquad (7)$$

The net mass backscattered from the MOLTRAP wall is 88.5 μg-pulse^{-1} or roughly 5.9% of the total mass (1.5 x 10^3 μg-pulse^{-1}) in the PPT plume. This net backscatter fraction is roughly five times smaller than the backscatter measured in the Fairchild vacuum facility,[4] primarily because of the anechoic baffling in MOLSINK.

3.4 SKIMMER BACKSCATTER DISTRIBUTION The data from the skirted on-axis skimmer (Figure 9) indicate that the backscatter from a localized plume segment is relatively non-uniform, due to the strong local changes in the slopes of the MOLTRAP walls. The overall backscatter is expected to be much more uniform since it represents an integrated value of the entire wall. This integrating effect can be seen in the data taken with the unskirted on-axis skimmer shown in Figure 12. The backscatter flux into the skimmer for this Figure is due to the collimated beam and also from the plume impinging on the MOLTRAP area around the skimmer hemisphere. Figure 13 shows the on-axis skimmer data taken with the collimator lid closed, thus only the backscatter flowing around the skimmer edge is being collected. The data of Figures 12 and 13 are comparable, confirming that the collimated beam signal is negligible. The magnitude of the edge leakage flux is much larger than that of the collimator flux because the effective source area is much greater. These data suggest that the overall backscatter distribution from the entire 40° half angle MOLTRAP wall region is approximately uniform. Furthermore, this implies that for distances well away from the wall-backscatter region, the backscattered flux can be taken as coming from a point source on the thruster axis at the MOLTRAP wall.

Some support for this conclusion can be found in the data obtained from the unskirted off-axis skimmer. This information is shown in Figure 14 where the QCM signals are plotted versus angle from the skimmer collimator axis. This

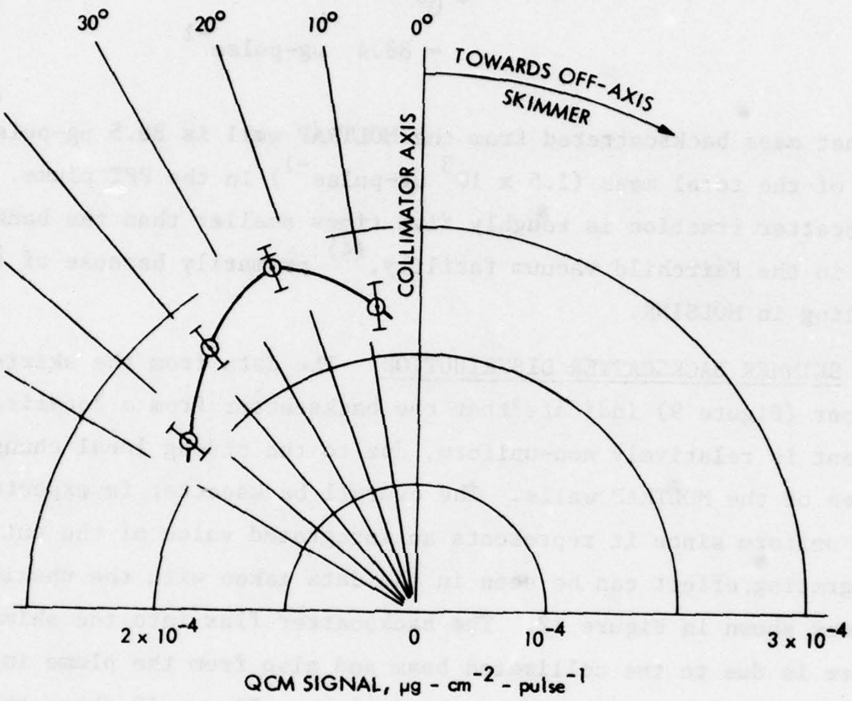

Figure 12. On-Axis Skimmer Backscatter (Lid Open, Unskirted Base)

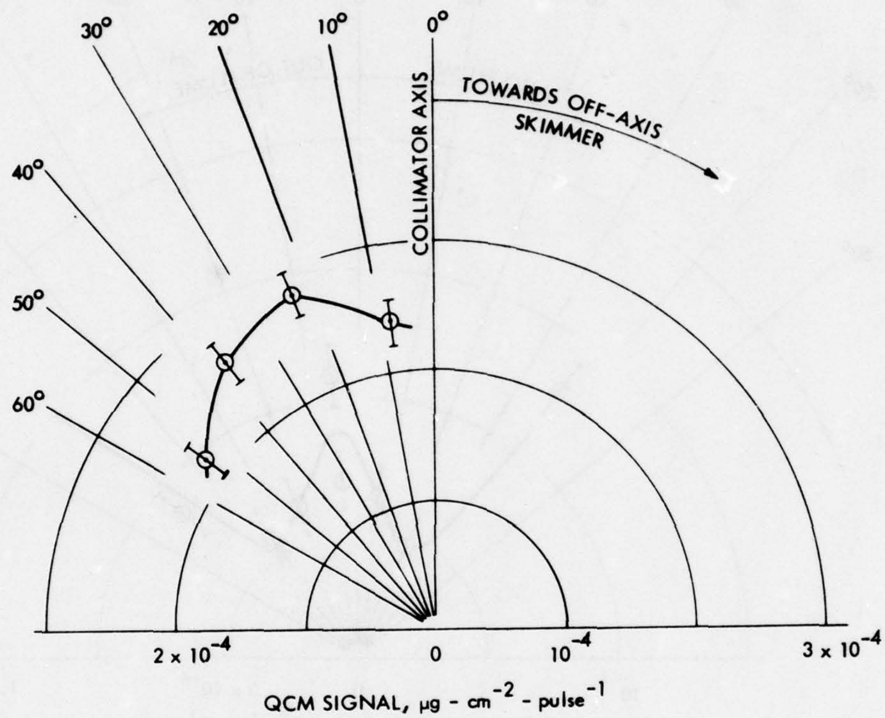

Figure 13. On-Axis Skimmer Backscatter (Lid Closed, Unskirted Base)

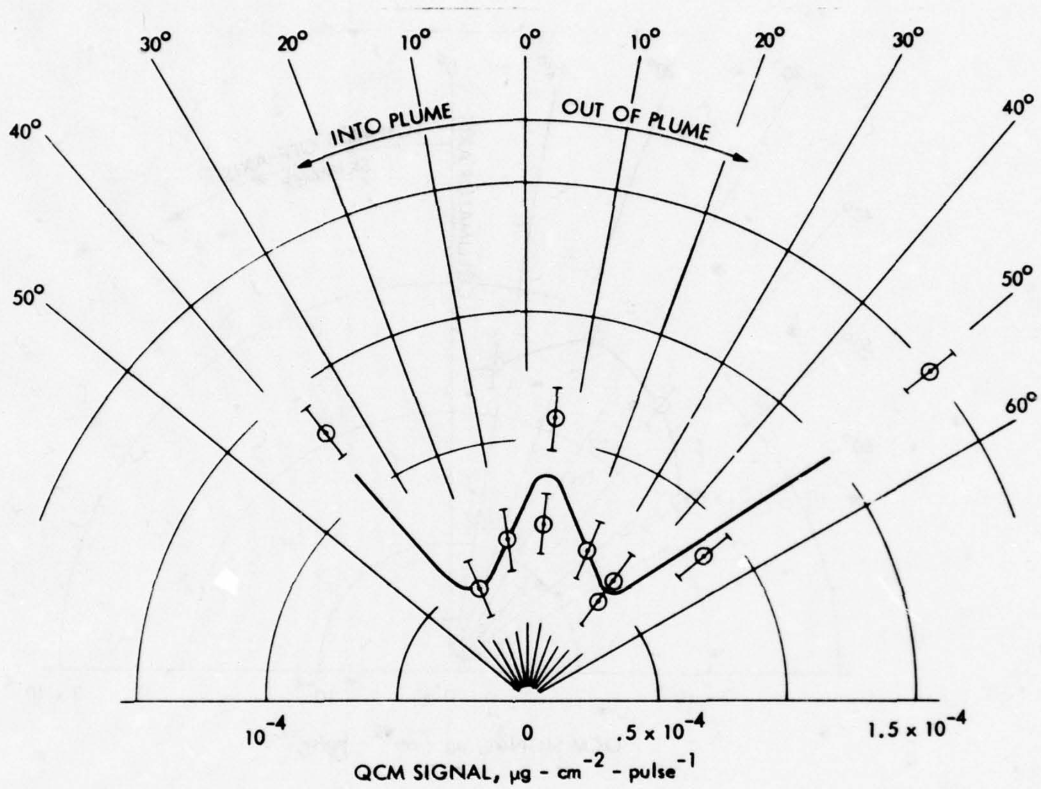

Figure 14. Off-Axis Skimmer Backscatter (Lid Open, Unskirted Base)

axis is directed along a 40° line from the PPT nozzle and is such that clockwise angles in this figure indicate directions out of the plume, while counterclockwise angles indicate directions toward the plume center. These data show a mass flux distribution symmetric about a 5° angle out of the plume. The net signal represents contributions primarily from backscatter flowing underneath the skimmer hemisphere edge, since the skirted, off-axis skimmer measurements are negligible. The backscatter flow into the off-axis skimmer is strongest on the lower side closest to the plume axis as evidenced by the 5° offset in the flux data. Even with this non-uniform incoming flux, the measured distribution of Figure 14 is much more uniform than that of Figure 9 indicating that the backscatter does indeed reach a reasonably uniform angular distribution about the plume axis.

Additional evidence on the wall-backscatter flow distribution can be found by examining the erosion-deposition patterns on the skimmer collimators after their removal from the test environment. Figure 15 shows a photograph of the on-axis skimmer collimator after the MOLSINK test. At the start of this test the collimator cones had a black anodized finish. As seen in Figure 15, the upper cone has remained clean while the lower two cones have multicolored patterns over their upper surfaces out from about 1 cm from the collimator hole. The colored patterns are attributed to thin, variable depth deposits of plume material. The clean regions around the edges of the cone collimator holes and over the entire top cone are due to the "scrubbing" action of the high energy plume as it strikes these surfaces and is collimated by them. The deposits must be due to material scattered from the MOLSINK walls or other surfaces and not from material coming directly from the plume. Thus, the multicolored patterns give a qualitative measure of the wall-backscatter distribution.

The patterns on the on-axis skimmer collimator seen in Figure 15 are concentric about the plume axis, indicating that the backscatter is symmetric about this axis. The patterns on the off-axis skimmer were observed only on the side closest to the plume axis, indicating that, as expected, the wall backscatter comes from within the 40° half-angle plume. In addition, some deposits were seen on the off-axis collimator top cone, indicating that the

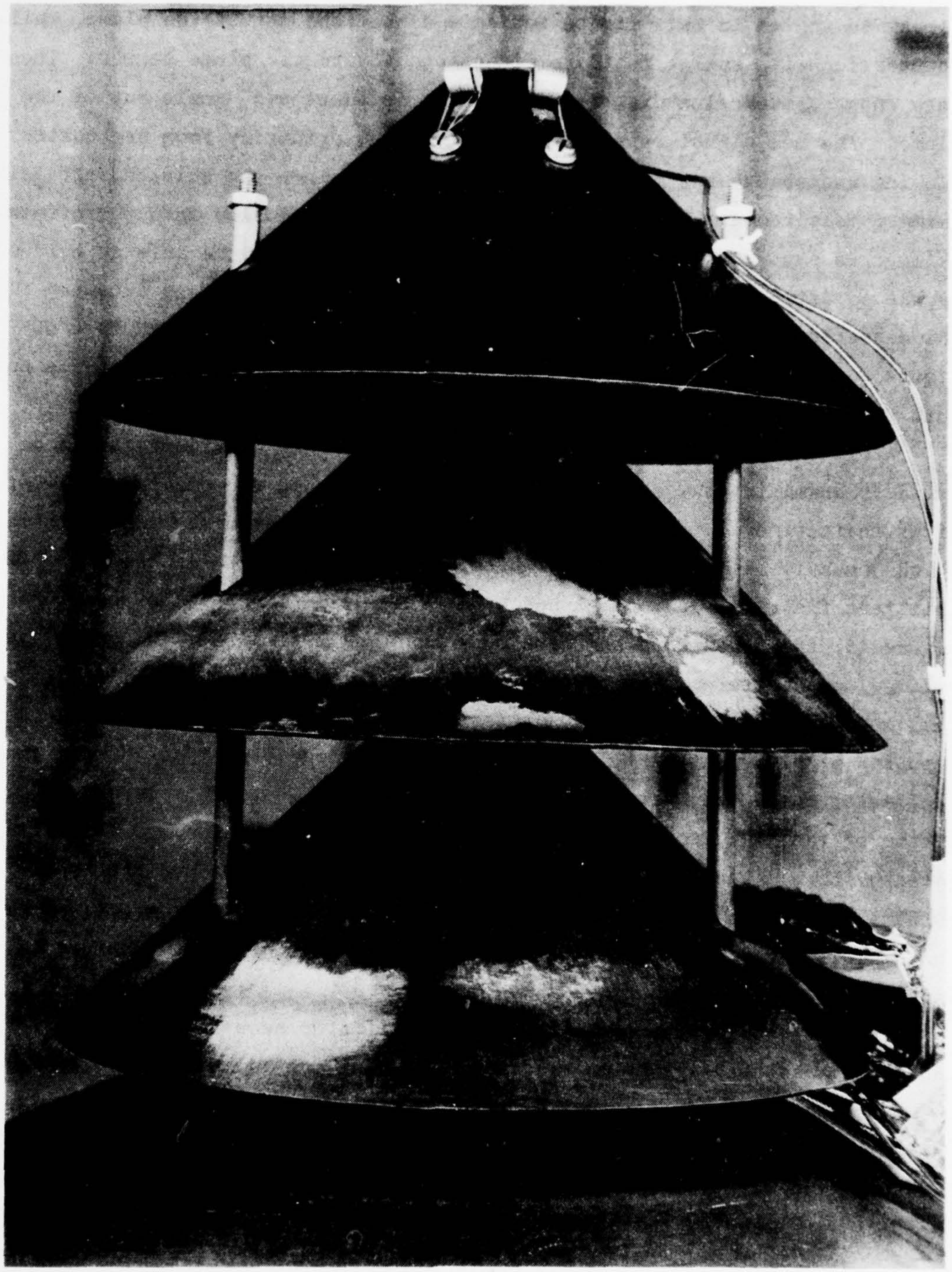

Figure 15. On-Axis Collimator Deposits

PPT plume "scrubbing" action is minimal and implying that the plume density is very low beyond 40° from the plume axis. This, again, is consistent with earlier conclusions.

The data taken with the unskirted on- and off-axis skimmers must be strongly affected by the presence of the skimmers themselves (see Table II), thus any conclusions about the behavior of the backscatter in MOLSINK in its usual configuration (without the skimmers) must be approximate. These data indicate general trends, at best, and must be taken in that light.

The picture that emerges from all the previous discussion is that the backscattered material from the plume-tank wall interaction originates in a region on the MOLTRAP wall bounded by the 40° half angle plume. The PPT plume is almost totally absorbed, with only 5.9% of the flux becoming backscatter. This backscatter flows upstream away from the wall in an approximately uniform distribution about the plume axis, and must eventually collide with the thruster and the upper MOLTRAP walls.

As a further check on this expected backscatter behavior, the net backscatter flux into the background QCM's behind the thruster (see Section 3.1) can be calculated and compared to the measured values. The backscatter flux at the MOLTRAP wall has been found to be 5.9% of the total plume mass or 88.4 μg-pulse^{-1}. Assuming a uniform distribution about a hemispherical surface centered on the plume axis-tank wall intersection with a radius equal to the distance to the background QCM's ($\sim$ 180 cm) gives an area of: $2\pi R^2 = 2.03 \times 10^5$ cm^2. This becomes a flux per unit area of: $88.4/2.03 \times 10^5 = 4.34 \times 10^{-4}$ μg-cm^{-2}-pulse^{-1}. This calculated backscatter flux should be compared to the first case in Table II where the backscatter at LN_2 temperatures without the skimmers was measured. This comparison indicates the calculated value is roughly four times as large as the measured value, which in the light of the assumptions made is a good agreement.

3.5 <u>SECONDARY BACKSCATTER</u> Once the backscatter flux reaches the upper wall area, it will undergo a second interaction with the MOLTRAP surface. Some will be absorbed while some may be reflected to continue to increase the general flux levels in MOLSINK. A measure of the 2nd bounce backscatter fraction can be found by considering the available data from the scanning QCM's mounted in the skimmers. These QCM's were mounted facing up towards the

skimmer hemispherical domes, such that, when in a position outside of the collimated beams, the net signal from them is due to backscattered material from the MOLTRAP wall that has either arrived directly or bounced once from the inner hemisphere wall.

Referring to Figure 16, the net output signal, S_1, from a QCM mounted on the skimmer surface is given by:

$$S_1 = \dot{m}_1 - \dot{m}_2 \tag{8}$$

where $\dot{m}_1$ is the backscatter from the first PPT plume-MOLTRAP wall interaction and $\dot{m}_2$ is the second bounce backscatter off the QCM surface. The net output signal, S_2, from the scanning QCM is given by:

$$S_2 = k\dot{m}_1 + \dot{m}_2 \tag{9}$$

where k is the fraction of backscatter reaching this QCM compared to the hemisphere QCM. These equations assume no third bounce flux comes off the scanning QCM.

The fraction k must be less than one since the scanning QCM is well off to the side of the original backscatter source, while the hemisphere QCM is in a much better location.

Equations (5) and (6) represent a system with three unknowns, $\dot{m}_1$, $\dot{m}_2$, and k. To solve this system one of these unknowns must be specified a priori. Because k is bounded from zero to one, it will be assumed equal to zero for a worst case analysis. Thus:

$$\begin{aligned} S_2 &= \dot{m}_2 \\ S_1 &= \dot{m}_1 - \dot{m}_2 \end{aligned} \tag{10}$$

The results from Figure 9 indicate the average hemisphere QCM signal is 2.5×10^{-5} µg-cm^{-2}-pulse^{-1}. This value will be taken as S_1. The measured

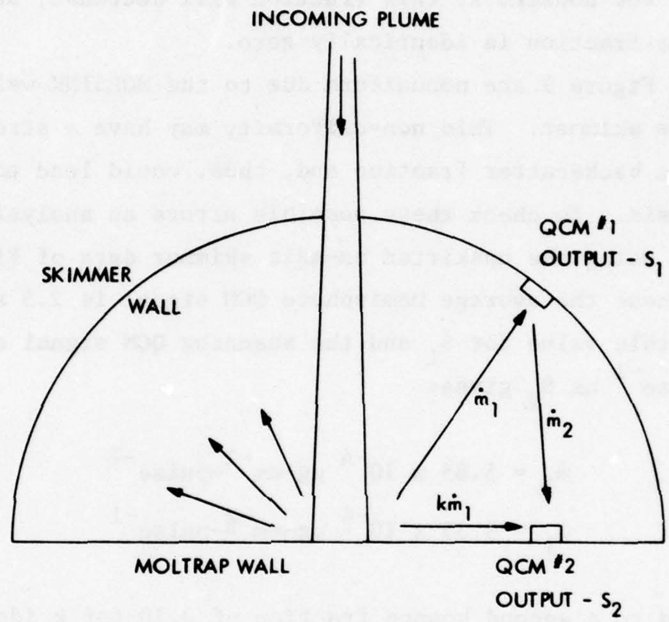

Figure 16. Second Bounce Schematic

value of S_2 for the same experimental parameters is 1.91×10^{-5} μg-cm^{-2}-pulse^{-1}. Solving the previous system gives:

$$\dot{m}_2 = 1.91 \times 10^{-5} \ \mu\text{g-cm}^{-2}\text{-pulse}^{-1}$$

$$\dot{m}_1 = 4.41 \times 10^{-5} \ \mu\text{g-cm}^{-2}\text{-pulse}^{-1} \qquad (11)$$

Thus the second bounce backscatter fraction defined is $\dot{m}_2/\dot{m}_1$ equals 0.43, assuming $k = 0$. For nonzero k, this fraction will decrease, and for $k = 0.76$ the second bounce fraction is identically zero.

The data of Figure 9 are nonuniform due to the MOLSINK wall construction under the on-axis skimmer. This non-uniformity may have a strong effect on the second bounce backscatter fraction and, thus, could lead to errors in the proceeding analysis. To check these possible errors an analysis identical to the previous one using the unskirted on-axis skimmer data of Figure 12 may be used. For this case the average hemisphere QCM signal is 2.5×10^{-4} μg-cm^{-2}-pulse^{-1}. Using this value for S_1 and the scanning QCM signal equal to 5.8×10^{-4} μg-cm^{-2}-pulse^{-1} as S_2 gives:

$$\dot{m}_2 = 5.85 \times 10^{-4} \ \mu\text{g-cm}^{-2}\text{-pulse}^{-1}$$

$$\dot{m}_1 = 8.35 \times 10^{-4} \ \mu\text{g-cm}^{-2}\text{-pulse}^{-1} \qquad (12)$$

These values lead to a second bounce fraction of 0.70 for k identically zero; however, for this experimental situation k must be greater than zero, since the scanning QCM is in a good position to get input flux directly from the backscatter around the skimmer lower edge. Assuming $k = 1$ gives:

$$\dot{m}_2 = 1.67 \times 10^{-4} \ \mu\text{g-cm}^{2}\text{-pulse}^{-1}$$

$$\dot{m}_1 = 4.17 \times 10^{-4} \ \mu\text{g-cm}^{-2}\text{-pulse}^{-1}$$

and the second bounce fraction becomes 0.40. These two values of the second bounce fraction (0.40 and 0.70) include the value of 0.43 found from the data of Figure 9 and indicate that in general the second bounce backscatter fraction is around 0.40.

4.0 PLANNED FUTURE WORK

The second phase of this effort will be a study of the PPT plume-spacecraft interaction utilizing the MOLSINK facility for measurements of the plume backflow mass flux into the thruster plane at various distances from the thruster axis, and of the PPT plume mass flux profile downstream of the thruster nozzle.

Because of the relatively large PPT plume backscatter in the MOLSINK over the wall areas directly in the PPT beam, a direct measurement of the plume backflow is impossible. Based on the understanding developed in this discussion and on the Fairchild plume study,[4] it is possible to develop an indirect method using collimated QCM's which can measure the backflow without being effected by the backscattered flux.

Figure 17 shows the proposed technique for measuring the backflow. In this design, a collimated QCM is rotated around a fixed point at the entrance of the collimator. The view angle of this QCM is finite, therefore the contributing volume is a cone with a volume element, dV. The insert in Figure 17 indicates the kind of data that should be derived from such a measurement. Note that the greatest backflow would be expected at 90°--decreasing to a lower value in the downstream direction. However, it is expected that the backscatter from the walls will predominate when the view of the QCM includes areas on the wall where the most energetic exhaust particles collide. When the distance from the exhaust plane to focal point of the QCM array (distance x in Figure 17) is increased it would be expected that the backflow measured would decrease because the density (or collision probability) is decreasing in the plume. This idea is shown in Figure 18. Note that the backscatter from the walls would be expected to increase because the QCM's are positioned closer to the wall.

The interpretation of these data in terms of total backflow depends on some understanding of the mass distribution in the plume, i.e., the relationship between the mass flux and the angle from the thruster axis. The collimated QCM views a volume of approximately conical shape. Each volume element within this cone has a density and angular orientation to the primary beam unique to its position and a specific solid angle with respect to the QCM;

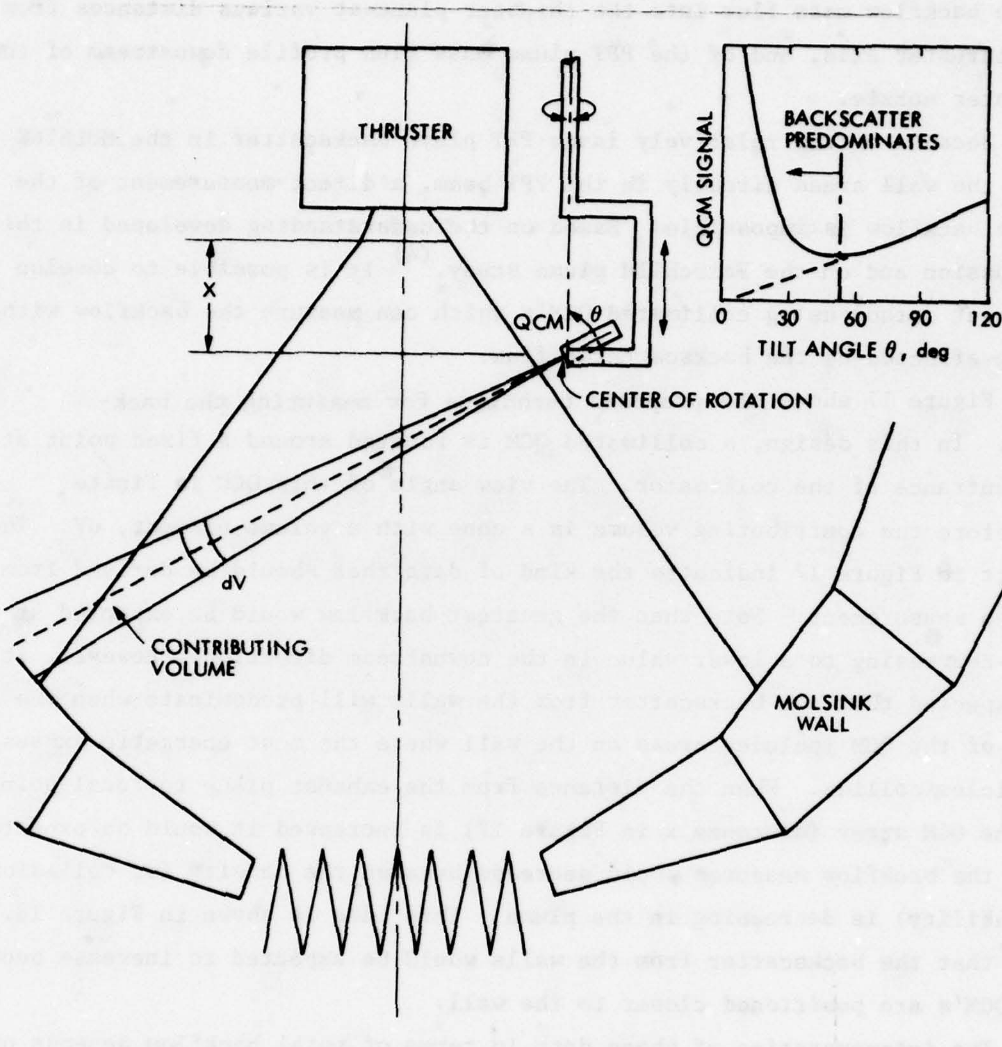

Figure 17. Backflow Measuring Technique

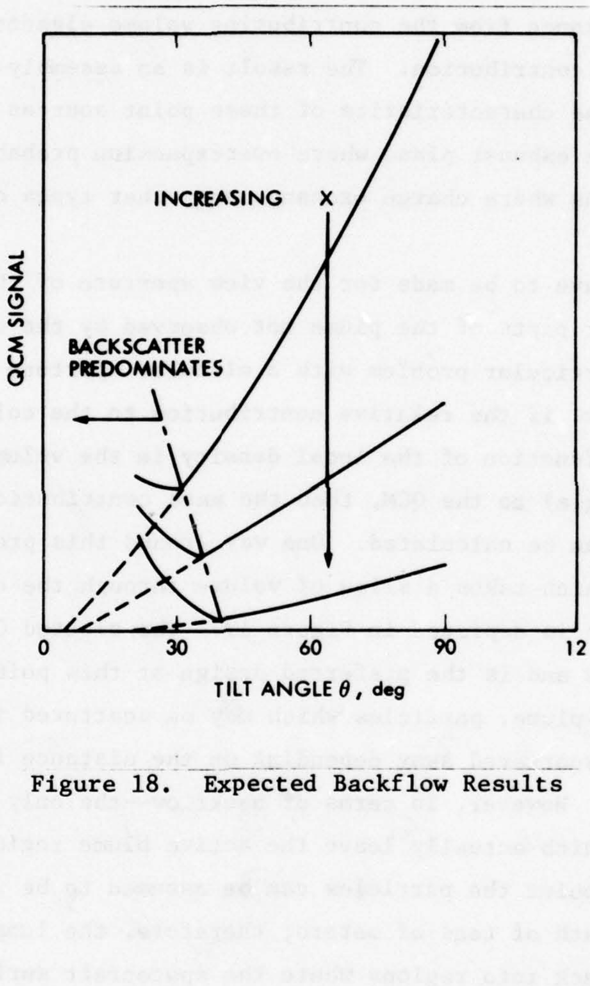

Figure 18. Expected Backflow Results

therefore, a knowledge of the primary mass distribution is needed to properly weigh the contributions from each volume element. A more detailed understanding would require the density distributions as a function of time during the firing process; however, this is beyond the scope of this effort.

The simplest approach of analysis is to use the lumped source technique which is a method of normalizing the flux measured at various angles to account for the different view volumes. Subsequently, the source is lumped at the focal point along the axis. A refinement of this would be to take account of the distance from the contributing volume element and the QCM to weigh the relative contribution. The result is an assembly of point sources along the axis. The characteristics of these point sources would vary from the region near the exhaust plane where overexpansion probably occurs to the downstream positions where charge exchange and other types of collisions would predominate.

Corrections have to be made for the view aperture of the collimated QCM to take account for parts of the plume not observed by the collimated probe. This would be a particular problem with a circular aperture as shown in Figure 19. However, if the relative contribution to the collimated QCM can be evaluated as a function of the local density in the volume element and the distance (solid angle) to the QCM, then the mass contribution coming from the remaining volume can be calculated. One way around this problem is to use a slotted view QCM which takes a slice of volume through the entire active plume region. This is depicted in Figure 19. The slotted QCM has many attractive features and is the preferred design at this point.

In the actual plume, particles which may be scattered in the direction of the QCM may be scattered away depending on the distance from the QCM and the local density. However, in terms of backflow--the only important particles are those which actually leave the active plume region and strike the QCM. Beyond that point the particles can be assumed to be in molecular flow with a mean free path of tens of meters; therefore, the lumped point sources can be projected back into regions where the spacecraft surfaces might be present.

Approximately five measurements along the thruster axis, say at 10 cm intervals beginning at the exhaust plane, should be able to quantify the major source of backflow. As shown in Figure 18, it may be possible to make

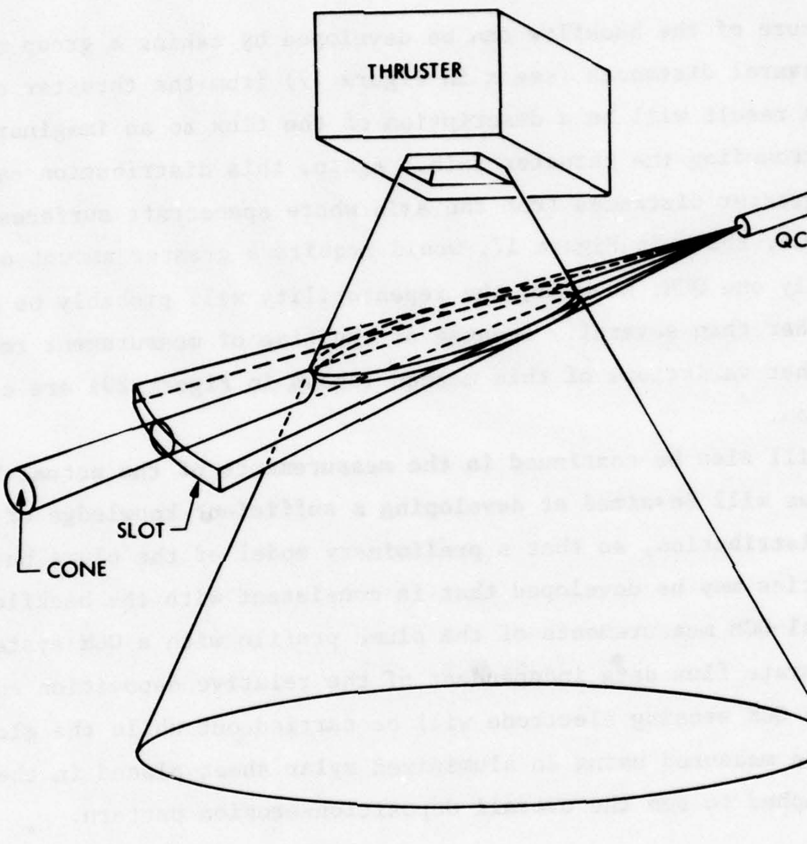

Figure 19. QCM View Volumes

a reasonable extrapolation of the data to account for the measurements when the backscatter from the wall predominates. Corrections have to be made to account for the change in projected area with the cosine of the angle with respect to the surface normal vector. Evaluation should be reasonably simple with this technique because the contribution from each solid angle with respect to the area element can be directly measured or extrapolated between measurements.

A picture of the backflow can be developed by taking a group of measurements at several distances (see x in Figure 17) from the thruster exhaust plane. The result will be a description of the flux to an imaginary cylindrical surface surrounding the thruster axis. Again, this distribution can be projected to greater distances from the axis where spacecraft surfaces may reside. The technique, shown in Figure 17, would require a greater amount of time because there is only one QCM; however, the repeatability will probably be better with one QCM rather than several. Because of the time of measurement required with one QCM, other variations of this method (shown in Figure 20) are also under consideration.

Work will also be continued in the measurements of the actual PPT plume. These studies will be aimed at developing a sufficient knowledge of the plume mass flux distribution, so that a preliminary model of the plume backflow characteristics may be developed that is consistent with the backflow measurements. Local QCM measurements of the plume profile with a QCM system designed to give accurate flux data independent of the relative deposition and erosion rates of the QCM sensing electrode will be carried out while the global plume shape will be measured using an aluminized mylar sheet placed in the PPT plume and photographed to see the overall deposition-erosion pattern.

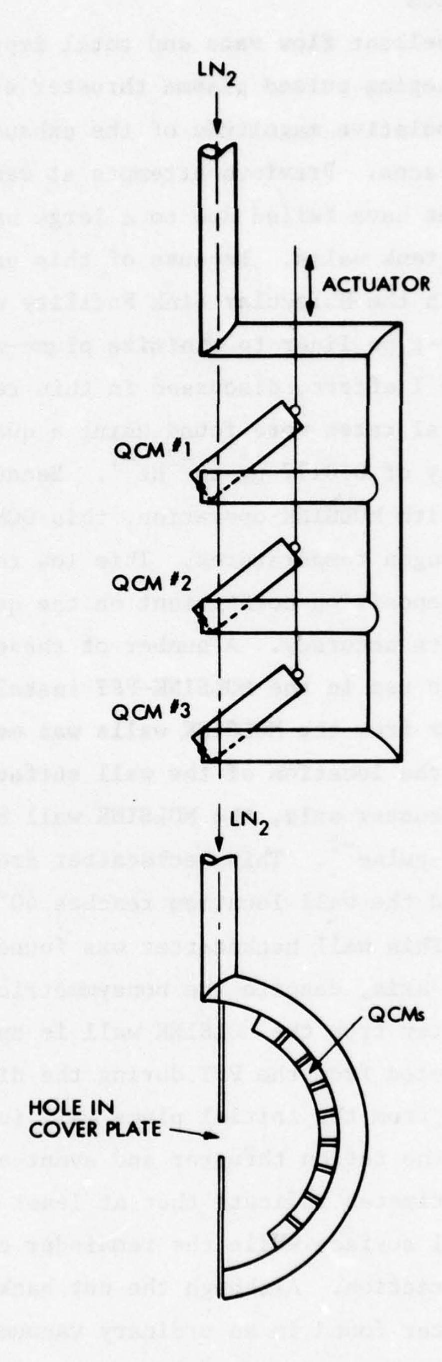

Figure 20. Backflow Measuring Options

5.0 SUMMARY AND CONCLUSION

Due to the high propellant flow rate and total impulse associated with the north-south stationkeeping pulsed plasma thruster system, questions have arisen concerning the cumulative magnitude of the exhaust plume backflow effect on spacecraft surfaces. Previous attempts at measuring this effect in ordinary vacuum facilities have failed due to a large backscatter of plume material from the vacuum tank walls. Because of this problem, studies have been initiated at JPL with the Molecular Sink Facility which uses a cryogenically cooled anechoic-type liner to minimize plume-wall backscatter. These studies include the Phase I effort, discussed in this report.

Local material arrival rates were found using a quartz crystal microbalance with a sensitivity of 0.0177 $\mu g\text{-}cm^{-2}Hz^{-1}$. Because of the cryogenic temperatures associated with MOLSINK operation, this QCM assembly was developed to operate at liquid nitrogen temperatures. This low temperature operation ensures a high material deposition coefficient on the quartz crystal sensing surface, thus improving its accuracy. A number of these QCM's were constructed and tested for use in the MOLSINK-PPT installation.

The total backscatter from the MOLSINK walls was measured and found to be strongly dependent on the location of the wall surface with respect to the thruster axis. On the thruster axis, the MOLSINK wall backscatter was found to be 1.23×10^{-2} $\mu g\text{-}cm^{-2}\text{-}pulse^{-1}$. This backscatter drops off to zero as the angle between the axis and the wall location reaches 40°, corresponding to the PPT plume boundary. This wall backscatter was found to be essentially symmetric about the plume axis, despite the nonsymmetric PPT nozzle. The total integrated backscatter from the MOLSINK wall is approximated equal to 5% of the total mass injected from the PPT during the discharge pulse.

The backscatter flux from the initial plume wall intersection flows directly back up towards the teflon thruster and eventually hits the upper MOLSINK wall surface. Estimates indicate that at least 50% of this flux is absorbed by the upper wall surface while the remainder continues to flow towards a third wall interaction. Although the net backscatter is less than one fifth of the backscatter found in an ordinary vacuum facility, it is still too large to allow a simple direct measurement of the PPT plume backflow.

Based on the measured plume-wall backscatter characteristics, an indirect method of measuring the net PPT plume backflow has been developed. This method is based on the use of collimated QCM's to observe selected regions of the PPT plume out of sight of the backscatter and will be used in the future Phase II of this study to evaluate the total plume backflow.

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APPENDIX A

PPT EXPERIMENTAL DATA

To determine the value of the mass flux to a given QCM, the frequency of this QCM must be monitored versus time for a sufficient period to allow an accurate determination of the rate of frequency shift. This rate is equal to the slope of the QCM frequency versus time curve (for example, see Figure 8, page 22) and is found by a linear regression analysis. It is then multiplied by the QCM calibration constant (1.77×10^{-8} g-cm^{-2}-Hz^{-1}) to give the QCM mass flux. For each mass flux quoted in the main body of this report (see Figures 8, 9, 12, 13, 14, and 16), there exists a series of QCM frequency measurements over time used to calculate this value. This appendix contains, for reference, a tabulation of these raw QCM frequency data.

To develop an accurate picture of the MOLSINK-PPT backscatter, tests were run under several experimental conditions. These conditions included changes in thruster position and pulse rate as well as changes in skimmer operation (skirted or unskirted, open or closed lids, etc.). They are discussed in detail in the main body of this report. In this appendix, the QCM data are separated into seven major conditions, with each condition described prior to each data table. These tables contain only those data actually used to calculate the QCM fluxes discussed in the main report. The remainder of the data are judged to be invalid due to various problems with the test operation.

For the first two experimental conditions, the QCM data were taken by hand, while, for the remainder, the data were automatically recorded on paper tape and printed out with a teletype-printer. This automatic recording system not only monitored the time and QCM frequencies but also monitored the outputs of 27 type T thermocouples located throughout the MOLSINK environment, including the QCM's themselves. The thermocouple data were recorded on output channels 1 through 27 while channels 0, 49, and 50 were used as calibration test outputs.

The following data tables include printouts of this thermocouple data, although only the time and QCM frequencies are relevant here. The time was measured with a 24 hour clock in hours, minutes and seconds and is printed out on channel 22 with a prefix T. The QCM frequencies, in hertz, are recorded on data channels 51 through 67 and have an F prefix. The particular channel number corresponding to a given QCM is shown in Figure A-1.

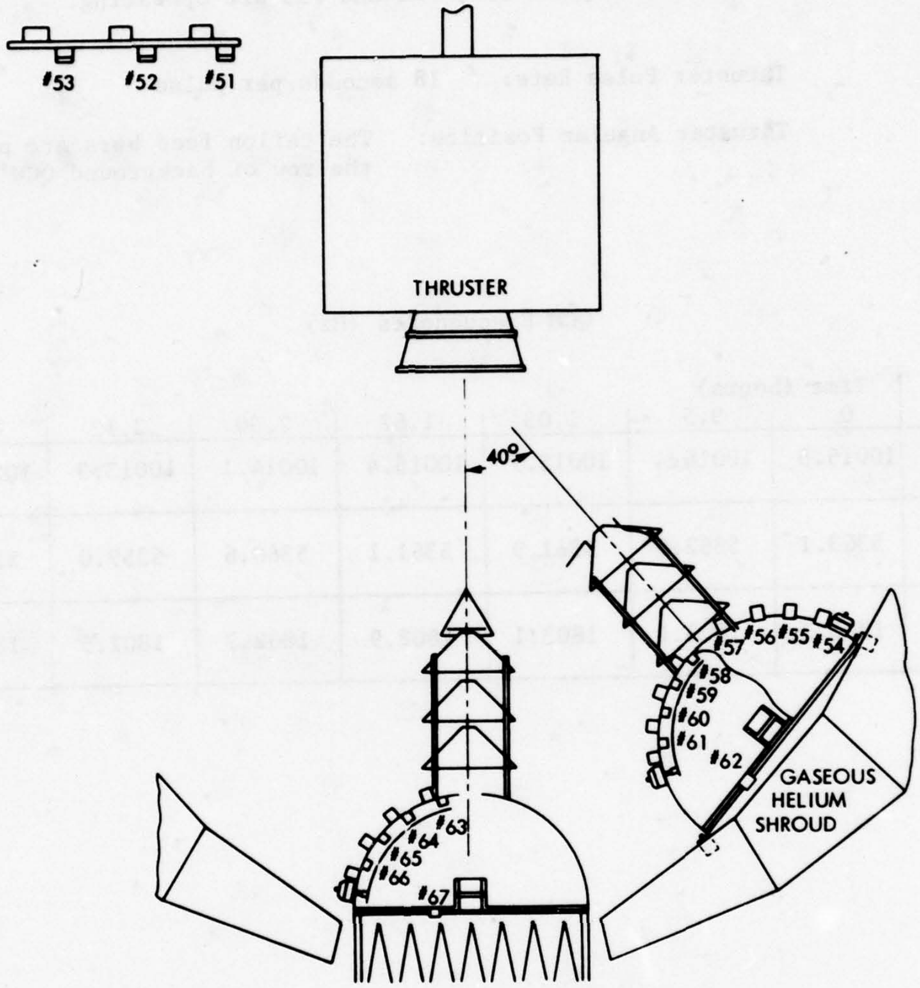

Figure A-1. QCM Number and Location

TEST CONDITION 1

Set-Up: The skimmers are not installed. Only the background QCM's #51, #52 and #53 are operating.

Thruster Pulse Rate: 18 seconds per pulse

Thruster Angular Position: The teflon feed bars are parallel to the row of background QCM's.

QCM Frequencies (Hz)

QCM #	Time (hours) 0	0.5	1.03	1.62	2.30	3.12	4.53	5.0
51	10016.8	10016.4	10015.9	10015.4	10014.1	10013.3	10012.1	10011.3
52	5363.1	5362.6	5361.9	5361.1	5360.6	5359.0	5356.9	5355.8
53	1803.3	1803.1	1803.1	1802.9	1802.7	1802.5	1802.2	1802.1

TEST CONDITION 2

Set-Up: See Condition 1.

Thruster Pulse Rate: 18 seconds per pulse.

Thruster Angular Position: To teflon feed bars are perpendicular to the row of background QCM's.

QCM Frequencies (Hz)

QCM #	Time (hours) 0	0.58	1.23	1.98	2.48	2.98	3.48
51	10010.6	10010.0	10008.7	10008.2	10007.5	10006.9	10006.2
52	5355.0	5354.3	5353.7	5302.9	5352.4	5351.9	5351.3
53	1801.8	1801.4	1800.9	1800.5	1800.2	1799.6	1799.2

TEST CONDITION 3

Set-Up: The skimmers are installed with all 17 QCMs. They are not skirted. QCM's #62 and #67 are giving spurious data.

Thruster Pulse Rate: 36 seconds per pulse.

Thruster Angular Position: See Condition 2.

```
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 061 0F0000003 062 0F0055303 063 0F0039453 064 0F0050763 065 0F0031863
 066 0F0019973 067 0F0000003
222  T080000  000 0+0000095 001 0-0055176 002 0-0053206 003 0-0052396
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 014 0-0045676 015 0-0045656 016 0-0044956 017 0-0041966 018 0+0006506
 020 0-0046896 021 0-0053686 022 0-0026966 023 0-0048946 024 0-0039936
 025 0-0050236 026 0-0034026 027 0-0057906 049 0+1000048 050 0-1000008
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 066 0F0019923 067 0F0000003
222  T090000  000 0+0000085 001 0-0055136 002 0-0053086 003 0-0052376
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 014 0-0045796 015 0-0045796 016 0-0045086 017 0-0042196 018 0+0006456
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 025 0-0050206 026 0-0033856 027 0-0057876 049 0+1000038 050 0-1000008
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 056 0F0088413 057 0F0000003 058 0F0000003 059 0F0189843 060 0F0000013
 061 0F0000003 062 0F0055363 063 0F0039413 064 0F0050743 065 0F0031823
 066 0F0019913 067 0F0000003
```

TEST CONDITION 4

Set-Up: The on-axis skimmer has a closed lid. QCM's #62 and #67 are in their parked positions next to the skimmer walls.

Thruster Pulse Rate: 36 seconds per pulse.

Thruster Angular Position: See Condition 2.

```
222  T154529  000 0+0000076 001 0-0056026 002 0-0054476 003 0-0052726
004 0-0042986 005 0-0043616 007 0-0044826 008 0-0046976 009 0-0047336
010 0-0047216 011 0-0044186 012 0-0041306 013 0-0047936 014 0-0048046
015 0-0047946 016 0-0047246 017 0-0041446 018 0+0005946 019 0-0025336
020 0-0052026 021 0-0058816 023 0-0053416 024 0-0032866 025 0-0053416
026 0-0043926 027 0-0046256 028 0-0046956 029 0-0049826 030 0-0048236
031 0-0047986 032 0-0046216 033 0-0054096 034 0-0058796 035 0-0061336
049 0+1000078 050 0-1000018 051 0F0097983 052 0F0050863 053 0F0019233
054 0F0000003 055 0F0016353 056 0F0000003 057 0F0000003 058 0F0048673
059 0F0189153 060 0F0000003 061 0F0103473 062 0F0055233 063 0F0037543
064 0F0048833 065 0F0030333 066 0F0018023 067 0F0000003
222  T160001  000 0+0000076 001 0-0056026 002 0-0054466 003 0-0052726
004 0-0042796 005 0-0043416 007 0-0046816 008 0-0046796 009 0-0047246
010 0-0047056 011 0-0043976 012 0-0041276 013 0-0047926 014 0-0048046
015 0-0047936 016 0-0047236 017 0-0041426 018 0+0005736 019 0-0021476
020 0-0052056 021 0-0058806 023 0-0053406 024 0-0032626 025 0-0053406
026 0-0043916 027 0-0046166 028 0-0046856 029 0-0049696 030 0-0048296
031 0-0047696 032 0-0046036 033 0-0054436 034 0-0058916 035 0-0061376
049 0+1000078 050 0-1000018 051 0F0097973 052 0F0050853 053 0F0019233
054 0F0000003 055 0F0016363 056 0F0000003 057 0F0045143 058 0F0048673
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222  T170001  000 0+0000076 001 0-0056036 002 0-0054486 003 0-0052856
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010 0-0046466 011 0-0043226 012 0-0041116 013 0-0047906 014 0-0048036
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020 0-0052456 021 0-0058796 023 0-0053396 024 0-0031736 025 0-0053406
026 0-0043896 027 0-0045476 028 0-0046176 029 0-0049276 030 0-0048316
031 0-0047126 032 0-0046116 033 0-0054356 034 0-0059506 035 0-0061366
049 0+1000088 050 0-1000018 051 0F0097953 052 0F0050833 053 0F0019213
054 0F0083193 055 0F0016353 056 0F0000003 057 0F0045133 058 0F0048683
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222  T170711  000 0+0000046 001 0-0056036 002 0-0054496 003 0-0052846
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054 0F0083193 055 0F0016353 056 0F0000003 057 0F0045133 058 0F0048673
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222  T180001  000 0+0000066 001 0-0056006 002 0-0054476 003 0-0052826
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015 0-0047916 016 0-0047216 017 0-0041446 018 0+0005596 019 0-0024546
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026 0-0043936 027 0-0044916 028 0-0045526 029 0-0048766 030 0-0048286
031 0-0046486 032 0-0045976 033 0-0054346 034 0-0059286 035 0-0061386
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064 0F0048813 065 0F0030333 066 0F0018003 067 0F0000003
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015 0-0047926 016 0-0047216 017 0-0041456 018 0+0005636 019 0-0022846
020 0-0052476 021 0-0058806 023 0-0053416 024 0-0030636 025 0-0053396
026 0-0043926 027 0-0044426 028 0-0045076 029 0-0048456 030 0-0048306
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222  T200447  000 0+0000036 001 0-0055996 002 0-0054456 003 0-0052786
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222  T201355  000 0-0000026 001 0-0055986 002 0-0054446 003 0-0052786
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222   T000001   000 0+0000046 001 0-0055956 002 0-0054426 003 0-0052756
004 0-0041916 005 0-0040576 007 0-0043966 008 0-0043786 009 0-0044496
010 0-0044176 011 0-0040956 012 0-0039896 013 0-0047846 014 0-0047966
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026 0-0044036 027 0-0042036 028 0-0042586 029 0-0046436 030 0-0048226
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064 0F0048683 065 0F0030213 066 0F0017853 067 0F0000003
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 010 0-0043546 011 0-0040396 012 0-00395P6 013 0-0047836 014 0-0047956
 015 0-0047856 016 0-0047136 017 0-0041396 018 0+0005696 019 0-0024036
 020 0-0052106 021 0-0058796 023 0-0053406 024 0-0028476 025 0-0053296
 026 0-0044026 027 0-0041936 028 0-0042496 029 0-0046356 030 0-0048196
 031 0-0043426 032 0-0045806 033 0-0054776 034 0-0059406 035 0-0061396
 049 0+1000078 050 0-1000038 051 0F0097693 052 0F0050583 053 0F0019033
 054 0F0082943 055 0F0016323 056 0F0000003 057 0F0044933 058 0F0048713
 059 0F0188903 060 0F0000003 061 0F0103643 062 0F0055193 063 0F0037393
 064 0F0048673 065 0F0030203 066 0F0017843 067 0F0000003
222   T080001  000 0+0000056 001 0-0055916 002 0-0054376 003 0-0052696
 004 0-0041216 005 0-0039916 007 0-0043286 008 0-0043056 009 0-0043806
 010 0-0043506 011 0-0040316 012 0-0039486 013 0-0047806 014 0-0047936
 015 0-0047846 016 0-0047146 017 0-0041386 018 0+0005606 019 0-0023236
 020 0-0052236 021 0-0058796 023 0-0053416 024 0-0028536 025 0-0053296
 026 0-0044006 027 0-0041846 028 0-0042426 029 0-0046356 030 0-0048256
 031 0-0043366 032 0-0045786 033 0-0054716 034 0-0059386 035 0-0061356
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064 0F0048663 065 0F0030203 066 0F0017833 067 0F0000003
222   T090001  000 0+0000046 001 0-0055936 002 0-0054406 003 0-0052726
004 0-0041206 005 0-0039926 007 0-0043296 008 0-0043066 009 0-0043816
010 0-0043496 011 0-0040306 012 0-0039456 013 0-0047836 014 0-0047956
015 0-0047856 016 0-0047156 017 0-0041396 018 0+0005096 019 0-0023946
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026 0-0044056 027 0-0041816 028 0-0042396 029 0-0046316 030 0-0048246
031 0-0043316 032 0-0045806 033 0-0054546 034 0-0058886 035 0-0061386
049 0+1000078 050 0-1000028 051 0F0097653 052 0F0050543 053 0F0019013
054 0F0082933 055 0F0016323 056 0F0000003 057 0F0044933 058 0F0048713
059 0F0188893 060 0F0000003 061 0F0103643 062 0F0055203 063 0F0037373
064 0F0048653 065 0F0030183 066 0F0017823 067 0F0000003
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TEST CONDITION 5

Set-Up: See Condition 4.

Thruster Pulse Rate: 23 seconds per pulse.

Thruster Angular Position: See Condition 2.

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222  T120001  000 0+0000046 001 0-0055946 002 0-0054426 003 0-0052736
004 0-0041186 005 0-0039896 007 0-0043316 008 0-0043046 009 0-0043806
010 0-0043476 011 0-0040286 012 0-0039386 013 0-0047846 014 0-0047976
015 0-0047876 016 0-0047166 017 0-0041416 018 0+0005986 019 0-0025036
020 0-0052066 021 0-0058796 023 0-0053436 024 0-0029046 025 0-0053316
026 0-0044066 027 0-0041666 028 0-0042246 029 0-0046196 030 0-0048196
031 0-0043206 032 0-0045846 033 0-0055196 034 0-0060416 035 0-0061346
049 0+1000088 050 0-1000018 051 0F0097603 052 0F0050493 053 0F0018983
054 0F0082913 055 0F0016303 056 0F0000003 057 0F0044923 058 0F0048703
059 0F0188883 060 0F0000003 061 0F0103643 062 0F0055193 063 0F0037333
064 0F0048623 065 0F0030153 066 0F0017783 067 0F0000003
222  T121001  000 0+0000046 001 0-0055926 002 0-0054406 003 0-0052726
004 0-0041186 005 0-0039896 007 0-0043306 008 0-0043066 009 0-0043826
010 0-0043506 011 0-0040336 012 0-0039416 013 0-0047876 014 0-0047976
015 0-0047886 016 0-0047176 017 0-0041426 018 0+0005816 019 0-0026296
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031 0-0043236 032 0-0045896 033 0-0054956 034 0-0059836 035 0-0061356
049 0+1000088 050 0-1000008 051 0F0097593 052 0F0050493 053 0F0018973
054 0F0082913 055 0F0016303 056 0F0000003 057 0F0044933 058 0F0048703
059 0F0188893 060 0F0000003 061 0F0103643 062 0F0055193 063 0F0037333
064 0F0048613 065 0F0030143 066 0F0017793 067 0F0000003
222  T122001  000 0+0000026 001 0-0055956 002 0-0054426 003 0-0052736
004 0-0041206 005 0-0039896 007 0-0043316 008 0-0043056 009 0-0043806
010 0-0043506 011 0-0040336 012 0-0039406 013 0-0047846 014 0-0047966
015 0-0047866 016 0-0047156 017 0-0041426 018 0+0005956 019 0-0027516
020 0-0052146 021 0-0058786 023 0-0053426 024 0-0029106 025 0-0053306
026 0-0044076 027 0-0041676 028 0-0042216 029 0-0046186 030 0-0048226
031 0-0043226 032 0-0045896 033 0-0055266 034 0-0060046 035 0-0061336
049 0+1000088 050 0-1000018 051 0F0097593 052 0F0050483 053 0F0018983
054 0F0082903 055 0F0016303 056 0F0000003 057 0F0044923 058 0F0048703
059 0F0188893 060 0F0000003 061 0F0103643 062 0F0055183 063 0F0037333
064 0F0048613 065 0F0030153 066 0F0017783 067 0F0000003
222  T123001  000 0+0000026 001 0-0055936 002 0-0054426 003 0-0052736
004 0-0041196 005 0-0039896 007 0-0043306 008 0-0043066 009 0-0043826
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015 0-0047876 016 0-0047166 017 0-0041436 018 0+0005976 019 0-0027086
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064 0F0048613 065 0F0030143 066 0F0017773 067 0F0000003
222  T124001  000 0+0000036 001 0-0055956 002 0-0054426 003 0-0052746
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015 0-0047846 016 0-0047146 017 0-0041436 018 0+0005806 019 0-0024546
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026 0-0044096 027 0-0041786 028 0-0042326 029 0-0046216 030 0-0048256
031 0-0043316 032 0-0045936 033 0-0054876 034 0-0059506 035 0-0061386
049 0+1000078 050 0-1000008 051 0F0097573 052 0F0050473 053 0F0018973
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064 0F0048613 065 0F0030143 066 0F0017773 067 0F0000003
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222   T130001   000 0+0000046 001 0-0055936 002 0-0054406 003 0-0052686
004 0-0041156 005 0-0039876 007 0-0043296 008 0-0043046 009 0-0043796
010 0-0043486 011 0-0040306 012 0-0039386 013 0-0047786 014 0-0047916
015 0-0047816 016 0-0047116 017 0-0041426 018 0+0005446 019 0-0024836
020 0-0052416 021 0-0058806 023 0-0053426 024 0-0029216 025 0-0053316
026 0-0044066 027 0-0041666 028 0-0042256 029 0-0046176 030 0-0048156
031 0-0043246 032 0-0045896 033 0-0054466 034 0-0059606 035 0-0061376
049 0+1000088 050 0-1000018 051 0F0097573 052 0F0050463 053 0F0018963
054 0F0082903 055 0F0016293 056 0F0000003 057 0F0044923 058 0F0048703
059 0F0188883 060 0F0000003 061 0F0103633 062 0F0055183 063 0F0037333
064 0F0048613 065 0F0030133 066 0F0017763 067 0F0000003
222   T131001   000 0+0000036 001 0-0055956 002 0-0054426 003 0-0052726
004 0-0041196 005 0-0039886 007 0-0043306 008 0-0043056 009 0-0043826
010 0-0043496 011 0-0040316 012 0-0039386 013 0-0047776 014 0-0047896
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049 0+1000088 050 0-1000008 051 0F0097573 052 0F0050463 053 0F0018963
054 0F0082903 055 0F0016303 056 0F0000003 057 0F0044923 058 0F0048703
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222   T131428   000 0+0000016 001 0-0055946 002 0-0054426 003 0-0052716
004 0-0041186 005 0-0039876 007 0-0043306 008 0-0043056 009 0-0043806
010 0-0043496 011 0-0040326 012 0-0039396 013 0-0047766 014 0-0047896
015 0-0047796 016 0-0047096 017 0-0041436 018 0+0005986 019 0-0025566
020 0-0052156 021 0-0058816 023 0-0053446 024 0-0029266 025 0-0053326
026 0-0044026 027 0-0041726 028 0-0042286 029 0-0046176 030 0-0048196
031 0-0043286 032 0-0045886 033 0-0054796 034 0-0059596 035 0-0061376
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064 0F0048603 065 0F0030133 066 0F0017773 067 0F0000003
222   T140001   000 0+0000056 001 0-0055956 002 0-0054436 003 0-0052706
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026 0-0043966 027 0-0041716 028 0-0042266 029 0-0046206 030 0-0048236
031 0-0043276 032 0-0045926 033 0-0054746 034 0-0060346 035 0-0061386
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Ø1Ø Ø-ØØ43486 Ø11 Ø-ØØ4Ø356 Ø12 Ø-ØØ39356 Ø13 Ø-ØØ47646 Ø14 Ø-ØØ47796
Ø15 Ø-ØØ477Ø6 Ø16 Ø-ØØ46996 Ø17 Ø-ØØ414Ø6 Ø18 Ø+ØØØ6236 Ø19 Ø-ØØ21516
Ø2Ø Ø-ØØ51896 Ø21 Ø-ØØ58786 Ø23 Ø-ØØ53366 Ø24 Ø-ØØ29336 Ø25 Ø-ØØ53296
Ø26 Ø-ØØ43926 Ø27 Ø-ØØ41666 Ø28 Ø-ØØ42216 Ø29 Ø-ØØ46196 Ø3Ø Ø-ØØ48146
Ø31 Ø-ØØ43236 Ø32 Ø-ØØ45876 Ø33 Ø-ØØ54376 Ø34 Ø-ØØ59866 Ø35 Ø-ØØ61366
Ø49 Ø+1ØØØØ88 Ø5Ø Ø-1ØØØØØ8 Ø51 ØFØØ97513 Ø52 ØFØØ5Ø4Ø3 Ø53 ØFØØ18923
Ø54 ØFØØ82883 Ø55 ØFØØ16283 Ø56 ØFØØØØØØ3 Ø57 ØFØØ44923 Ø58 ØFØØ48693
Ø59 ØFØ188883 Ø6Ø ØFØØØØØØ3 Ø61 ØFØ1Ø3633 Ø62 ØFØØ55173 Ø63 ØFØØ37293
Ø64 ØFØØ48573 Ø65 ØFØØ3Ø113 Ø66 ØFØØ17743 Ø67 ØFØØØØØØ3
222  T16ØØØ1  ØØØ Ø+ØØØØ116 ØØ1 Ø-ØØ559Ø6 ØØ2 Ø-ØØ54396 ØØ3 Ø,ØØ52646
ØØ4 Ø-ØØ41126 ØØ5 Ø-ØØ39816 ØØ7 Ø-ØØ43256 ØØ8 Ø-ØØ43ØØ6 ØØ9 Ø-ØØ43776
Ø1Ø Ø-ØØ43456 Ø11 Ø-ØØ4Ø346 Ø12 Ø-ØØ39316 Ø13 Ø-ØØ47596 Ø14 Ø-ØØ47736
Ø15 Ø-ØØ47646 Ø16 Ø-ØØ46936 Ø17 Ø-ØØ41366 Ø18 Ø+ØØØ6256 Ø19 Ø-ØØ27Ø96
Ø2Ø Ø-ØØ52Ø86 Ø21 Ø-ØØ58746 Ø23 Ø-ØØ53326 Ø24 Ø-ØØ29296 Ø25 Ø-ØØ53266
Ø26 Ø-ØØ43856 Ø27 Ø-ØØ416Ø6 Ø28 Ø-ØØ42196 Ø29 Ø-ØØ46Ø86 Ø3Ø Ø-ØØ48Ø76
Ø31 Ø-ØØ43216 Ø32 Ø-ØØ45756 Ø33 Ø-ØØ54136 Ø34 Ø-ØØ59416 Ø35 Ø-ØØ61346
Ø49 Ø+1ØØØØ78 Ø5Ø Ø-1ØØØØ18 Ø51 ØFØØ97483 Ø52 ØFØØ5Ø373 Ø53 ØFØØ189Ø3
Ø54 ØFØØ82883 Ø55 ØFØØ16283 Ø56 ØFØØØØØØ3 Ø57 ØFØØ44913 Ø58 ØFØØ48693
Ø59 ØFØ188873 Ø6Ø ØFØØØØØØ3 Ø61 ØFØ1Ø3633 Ø62 ØFØØ55173 Ø63 ØFØØ37293
Ø64 ØFØØ48553 Ø65 ØFØØ3Ø1Ø3 Ø66 ØFØØ17733 Ø67 ØFØØØØØØ3
222  T17ØØØ1  ØØØ Ø+ØØØØ126 ØØ1 Ø-ØØ55926 ØØ2 Ø-ØØ544Ø6 Ø33 Ø-ØØ52656
ØØ4 Ø-ØØ41136 ØØ5 Ø-ØØ39816 ØØ7 Ø-ØØ43266 ØØ8 Ø-ØØ43Ø16 ØØ9 Ø-ØØ43776
Ø1Ø Ø-ØØ43456 Ø11 Ø-ØØ4Ø346 Ø12 Ø-ØØ39286 Ø13 Ø-ØØ47566 Ø14 Ø-ØØ47696
Ø15 Ø-ØØ476Ø6 Ø16 Ø-ØØ46896 Ø17 Ø-ØØ41316 Ø18 Ø+ØØØ6136 Ø19 Ø-ØØ21946
Ø2Ø Ø-ØØ51966 Ø21 Ø-ØØ58736 Ø23 Ø-ØØ53286 Ø24 Ø-ØØ292Ø6 Ø25 Ø-ØØ53266
Ø26 Ø-ØØ43846 Ø27 Ø-ØØ41666 Ø28 Ø-ØØ422Ø6 Ø29 Ø-ØØ46Ø86 Ø3Ø Ø-ØØ48Ø16
Ø31 Ø-ØØ43196 Ø32 Ø-ØØ45716 Ø33 Ø-ØØ54Ø86 Ø34 Ø-ØØ58676 Ø35 Ø-ØØ61366
Ø49 Ø+1ØØØØ88 Ø5Ø Ø-1ØØØØ18 Ø51 ØFØØ97463 Ø52 ØFØØ5Ø353 Ø53 ØFØØ18893
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Ø64 ØFØØ48553 Ø65 ØFØØ3ØØ93 Ø66 ØFØØ17713 Ø67 ØFØØØØØØ3
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ØØ4 Ø-ØØ41Ø76 ØØ5 Ø-ØØ39776 ØØ7 Ø-ØØ432Ø6 ØØ8 Ø-ØØ42966 ØØ9 Ø-ØØ437Ø6
Ø1Ø Ø-ØØ434Ø6 Ø11 Ø-ØØ4Ø296 Ø12 Ø-ØØ39236 Ø13 Ø-ØØ47496 Ø14 Ø-ØØ47646
Ø15 Ø-ØØ47546 Ø16 Ø-ØØ46836 Ø17 Ø-ØØ41286 Ø18 Ø+ØØØ5166 Ø19 Ø-ØØ23726
Ø2Ø Ø-ØØ52386 Ø21 Ø-ØØ58736 Ø23 Ø-ØØ53276 Ø24 Ø-ØØ29Ø96 Ø25 Ø-ØØ53246
Ø26 Ø-ØØ43816 Ø27 Ø-ØØ41566 Ø28 Ø-ØØ42156 Ø29 Ø-ØØ461Ø6 Ø3Ø Ø-ØØ47966
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Ø49 Ø+1ØØØØ78 Ø5Ø Ø-1ØØØØ28 Ø51 ØFØØ97433 Ø52 ØFØØ5Ø323 Ø53 ØFØØ18873
Ø54 ØFØØ82863 Ø55 ØFØØ16263 Ø56 ØFØØØØØØ3 Ø57 ØFØØ449Ø3 Ø58 ØFØØ48693
Ø59 ØFØ188863 Ø6Ø ØFØØØØØØ3 Ø61 ØFØ1Ø3633 Ø62 ØFØØ55173 Ø63 ØFØØ37273
Ø64 ØFØØ48533 Ø65 ØFØØ3ØØ83 Ø66 ØFØØ17713 Ø67 ØFØØØØØØ3
222  T19ØØØ1  ØØØ Ø+ØØØØ156 ØØ1 Ø-ØØ55896 ØØ2 Ø-ØØ54376 ØØ3 Ø-ØØ52656
ØØ4 Ø-ØØ41Ø76 ØØ5 Ø-ØØ39776 ØØ7 Ø-ØØ43176 ØØ8 Ø-ØØ42946 ØØ9 Ø-ØØ43716
Ø1Ø Ø-ØØ43386 Ø11 Ø-ØØ4Ø256 Ø12 Ø-ØØ392Ø6 Ø13 Ø-ØØ47486 Ø14 Ø-ØØ47616
Ø15 Ø-ØØ47536 Ø16 Ø-ØØ46826 Ø17 Ø-ØØ41256 Ø18 Ø+ØØØ6386 Ø19 Ø-ØØ23466
Ø2Ø Ø-ØØ51946 Ø21 Ø-ØØ58716 Ø23 Ø,ØØ53236 Ø24 Ø-ØØ28726 Ø25 Ø-ØØ53256
Ø26 Ø-ØØ43816 Ø27 Ø-ØØ41666 Ø28 Ø-ØØ42196 Ø29 Ø-ØØ46Ø96 Ø3Ø Ø-ØØ47946
Ø31 Ø-ØØ43216 Ø32 Ø-ØØ45676 Ø33 Ø-ØØ52956 Ø34 Ø-ØØ57936 Ø35 Ø-ØØ61376
Ø49 Ø+1ØØØØ78 Ø5Ø Ø-1ØØØØ38 Ø51 ØFØØ974Ø3 Ø52 ØFØØ5Ø3Ø3 Ø53 ØFØØ18853
Ø54 ØFØØ82853 Ø55 ØFØØ16253 Ø56 ØFØØØØØØ3 Ø57 ØFØØ449Ø3 Ø58 ØFØØ48683
Ø59 ØFØ188853 Ø6Ø ØFØØØØØØ3 Ø61 ØDØ1Ø3633 Ø62 ØFØØ55173 Ø63 ØFØØ37253
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054 0F0082843 055 0F0016243 056 0F0000003 057 0F0044893 058 0F0048683
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020 0-0052016 021 0,0058706 023 0-0053226 024 0-0028586 025 0-0053256
026 0-0043756 027 0-0041606 028 0-0042196 029 0-0046086 030 0-0047906
031 0-0043186 032 0-0045566 033 0-0053846 034 0-0058506 035 0-0061356
 049 0+1000078 050 0-1000038 051 0F0097363 052 0F0050273 053 0F0018833
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059 0F0188863 060 0F0000003 061 0F0103633 062 0F0055173 063 0F0037243
064 0F0048493 065 0F0030043 066 0F0017683 067 0F0000003
222  T201541  000 0+0000136 001 0-0055886 002 0-0054366 003 0-0052606
004 0-0041036 005 0-0039716 007 0-0043116 008 0-0042876 009 0-0043636
010 0-0043316 011 0-0040136 012 0-0039186 013 0-0047456 014 0-0047566
015 0-0047486 016 0-0046796 017 0-0041216 018 0+0006196 019 0-0019976
020 0-0052016 021 0-0058716 023 0-0053216 024 0-0028586 025 0-0053266
026 0-0043706 027 0-0041586 028 0-0042156 029 0-0046076 030 0-0047896
031 0-0043146 032 0-0045576 033 0-0053306 034 0-0058176 035 0-0061346
049 0+1000078 050 0-1000048 051 0F0097363 052 0F0050263 053 0F0018823
054 0F0082843 055 0F0016243 056 0F0000003 057 0F0044893 058 0F0048683
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 064 0F0048493 065 0F0030043 066 0F0017683 067 0F0000003
222  T210001  000 0+0000156 001 0-0055916 002 0-0054386 003 0-0052636
004 0-0041026 005 0-0039716 007 0-0043126 008 0-0042886 009 0-0043636
 010 0-0043316 011 0-0040116 012 0-0039196 013 0-0047456 014 0-0047576
 015 0-0047476 016 0-0046796 017 0-0041216 018 0+0005476 019 0-0026216
 020 0-0052306 021 0-0058726 023 0-0053226 024 0-0028526 025 0-0053266
 026 0-0043706 027 0-0041576 028 0-0042146 029 0-0046046 030 0-0047856
 031 0-0043086 032 0-0045506 033 0-0054036 034 0-0058736 035 0-0061386
 049 0+1000068 050 0-1000048 051 0F0097343 052 0F0050243 053 0F0018813
 054 0F0082833 055 0F0016233 056 0F0000003 057 0F0044883 058 0F0048683
 059 0F0188843 060 0F0000003 061 0F0103633 062 0F0055163 063 0F0037233
 064 0F0048473 065 0F0030033 066 0F0017673 067 0F0000003
222  T220001  000 0+0000166 001 0-0055926 002 0-0054396 003 0-0052656
004 0-0041026 005 0-0039716 007 0-0043126 008 0-0042866 009 0-0043616
010 0-0043296 011 0-0040126 012 0-00391X6 013 0-0047436 014 0-0047546
015 0-0047466 016 0-0046796 017 0-0041196 018 0+0006466 019 0-0023156
020 0-0051986 021 0-0058756 023 0-0053246 024 0-0028436 025 0-0053286
026 0-0043736 027 0-0041566 028 0-0042136 029 0-0046076 030 0-0047896
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222  T230001  000 0+0000166 001 0-0055916 002 0-0054396 003 0-0052656
004 0-0041006 005 0-0039696 007 0-0043106 008 0-0042846 009 0-0043596
010 0-0042276 011 0-0040086 012 0-0039176 013 0-0047416 014 0-0047536
015 0-0047456 016 0-0046776 017 0-0041196 018 0+0006396 019 0-0023056
020 0-0051856 021 0-0058756 023 0-0053226 024 0-0028296 025 0-0053276
026 0-0043656 027 0-0041496 028 0-0042086 029 0-0046046 030 0-0047936
031 0-0043106 032 0-0045426 033 0-0053786 034 0-0058016 035 0-0061376
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054 0F0082813 055 0F0016223 056 0F0000003 057 0F0044883 058 0F0048683
059 0F0188843 060 0F0000003 061 0F0103633 062 0F0055163 063 0F0037213
064 0F0048443 065 0F0030003 066 0F0017643 067 0F0000003
222  T000001  000 0+0000176 001 0-0055936 002 0-0054396 003 0-0052656
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015 0-0047456 016 0-0046776 017 0-0041196 018 0+0005886 019 0-0024666
020 0-0052126 021 0-0058766 023 0-0053246 024 0-0028166 025 0-0053296
026 0-0043696 027 0-0041536 028 0-0042126 029 0-0046106 030 0-0047936
031 0-0043116 032 0-0045446 033 0-0053666 034 0-0057996 035 0-0061426
049 0+1000058 050 0-1000058 051 0F0097253 052 0F0050153 053 0F0018753
054 0F0082813 055 0F0016223 056 0F0000003 057 0F0044883 058 0F0048673
059 0F0188843 060 0F0000013 061 0F0103623 062 0F0055163 063 0F0037193
064 0F0048433 065 0F0029983 066 0F0017633 067 0F0000003
222  T010001  000 0+0000176 001 0-0055926 002 0-0054396 003 0-0052656
004 0-0040986 005 0-0039666 007 0-0043066 008 0-0042806 009 0-0043556
010 0-0043226 011 0-0040086 012 0-0039166 013 0-0047426 014 0-0047546
015 0-0047466 016 0-0046786 017 0-0041206 018 0+0006386 019 0-0023966
020 0-0051936 021 0-0058766 023 0-0053236 024 0-0028056 025 0-0053286
026 0-0043586 027 0-0041426 028 0-0042026 029 0-0045996 030 0-0047846
031 0-0043006 032 0-0045326 033 0-0053556 034 0-0057876 035 0-0061426
049 0+1000058 050 0-1000068 051 0F0097233 052 0F0050123 053 0F0018743
054 0F0082793 055 0F0016213 056 0F0000003 057 0F0044873 058 0F0048673
059 0F0188843 060 0F0000003 061 0F0103623 062 0F0055153 063 0F0037183
064 0F0048413 065 0F0029973 066 0F0017613 067 0F0000003
222  T020001  000 0+0000216 001 0-0055906 002 0-0054366 003 0-005266
004 0-0040926 005 0-0039616 007 0-0043016 008 0-0042746 009 0-00435l
010 0-0043186 011 0-0040046 012 0-0039166 013 0-0047426 014 0-0047516
015 0-0047446 016 0-0046766 017 0-0041186 018 0+0006446 019 0-0023246
020 0-0051986 021 0-0058766 023 0-0053236 024 0-0027976 025 0-0053276
026 0-0043626 027 0-0041386 028 0-0041896 029 0-0045856 030 0-0047706
031 0-0042966 032 0-0045326 033 0-0053426 034 0-0058236 035 0-0061386
049 0+1000058 050 0-1000068 051 0F0097203 052 0F0050103 053 0F0018723
054 0F0082783 055 0F0016203 056 0F0000003 057 0F0044873 058 0F0048673
059 0F0188823 060 0F0000003 061 0F0103623 062 0F0055153 063 0F0037153
064 0F0048393 065 0F0029953 066 0F0017613 067 0F0000003
222  T030001  000 0+0000196 001 0-0055936 002 0-0054396 003 0-0052666
004 0-0040946 005 0-0039636 007 0-0043026 008 0-0042766 009 0-0043526
010 0-0043186 011 0-0040056 012 0-00391P6 013 0-0047406 014 0-0047516
015 0-0047436 016 0-0046746 017 0-0041186 018 0+0006366 019 0-0022836
020 0-0051896 021 0-0058766 023 0-0053246 024 0-0027976 025 0-0053296
026 0-0043586 027 0-0041366 028 0-0041966 029 0-0045976 030 0-0047856
031 0-0043176 032 0-0045426 033 0-0053146 034 0-0057696 035 0-0061396
049 0+1000058 050 0-1000068 051 0F0097173 052 0F0050073 053 0F0018703
054 0F0082783 055 0F0016193 056 0F0000003 057 0F0044853 058 0F0048663
059 0F0188823 060 0F0000003 061 0F0103623 062 0F0055153 063 0F0037153
064 0F0048373 065 0F0029943 066 0F0017593 067 0F0000003
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TEST CONDITION 6

Set-Up: The on-axis skimmer is skirted around its base. QCM's #62 and #67 are in their parked positions next to the skimmer walls.

Thruster Pulse Rate: 36 seconds per pulse.

Thruster Angular Position: See Condition 2.

222	T150000	000	0-0000096	001	0-0056376	002	0-0054766	003	0-0053106
004	0-0051156	005	0-0053346	006	0-0000476	007	0-0053026	008	0-0052996
009	0-0053356	010	0-0053326	011	0-0053086	012	0-0052786	013	0-0049996
014	0-0050596	015	0-0050506	016	0-0049706	017	0-0050586	018	0+0007916
019	0-0015956	020	0-0053676	021	0-0056846	023	0-0055156	024	0-0049026
025	0-0053066	026	0-0045656	027	0-0053016	028	0-0053356	029	0-0054066
030	0-0051116	031	0-0053426	032	0-0050556	033	0-0056836	035	0-0061586
049	0+1000108	050	0-0999958	051	0F0097133	052	0F0049823	053	0F0018873
054	0F0000003	055	0F0015903	056	0F0000383	057	0F0000003	058	0F0048523
059	0F0190163	060	0F0031743	061	0F0102783	062	0F0023673	063	0F0039463
064	0F0050513	065	0F0030813	066	0F0019403	067	0F0000003		
222	T150200	000	0-0000136	001	0-0056186	002	0-0054566	003	0-0052886
004	0-0050976	005	0-0053156	006	0-0000286	007	0-0052856	008	0-0052836
009	0-0053446	010	0-0053166	011	0-0052926	012	0-0052626	013	0-0049846
014	0-0050436	015	0-0050356	016	0-0049566	017	0-0050446	018	0+0007866
019	0-0019386	020	0-0053616	021	0-0056706	023	0-0055046	024	0-0048906
025	0-0053076	026	0-0045666	027	0-0053026	028	0-0053356	029	0-0054056
030	0-0051116	031	0-0053426	032	0-0050566	033	0-0056596	035	0-0061596
049	0+1000118	050	0-0999968	051	0F0097133	052	0F0049823	053	0F0018873
054	0F0000003	055	0F0015903	056	0F0000373	057	0F0000003	058	0F0048523
059	0F0190153	060	0F0031743	061	0F0102773	062	0F0024213	063	0F0039463
064	0F0050513	065	0F0030813	066	0F0019403	067	0F0000003		
222	T150400	000	0-0000146	001	0-0056246	002	0-0054626	003	0-0052906
004	0-0051016	005	0-0053206	006	0-0000346	007	0-0052876	008	0-0052846
009	0-0053226	010	0-0053196	011	0-0052966	012	0-0052666	013	0-0049886
014	0-0050476	015	0-0050396	016	0-0049596	017	0-0050496	018	0+0008036
019	0-0021506	020	0-0053566	021	0-0056756	023	0-0055086	024	0-0048936
025	0-0053066	026	0-0045656	027	0-0053026	028	0-0053356	029	0-0054066
030	0-0051106	031	0-0053426	032	0-0050556	033	0-0056696	035	0-0061576
049	0+1000118	050	0-0999968	051	0F0097133	052	0F0049823	053	0F0018873
054	0F0000003	055	0F0015913	056	0F0000433	057	0F0000003	058	0F0048513
059	0F0190163	060	0F0031743	061	0F0102773	062	0F0022673	063	0F0039463
064	0F0050513	065	0F0030803	066	0F0019413	067	0F0000003		
222	T150600	000	0-0000126	001	0-0056266	002	0-0054646	003	0-0052966
004	0-0051046	005	0-0053246	006	0-0000366	007	0-0052926	008	0-0052906
009	0-0053256	010	0-0053236	011	0-0053026	012	0-0052716	013	0-0049936
014	0-0050536	015	0-0050456	016	0-0049646	017	0-0050536	018	0+0007706
019	0-0017236	020	0-0053676	021	0-0056786	023	0-0055136	024	0-0048976
025	0-0053066	026	0-0045646	027	0-0052996	028	0-0053326	029	0-0054026
030	0-0051086	031	0-0053426	032	0-0050546	033	0-0056456	035	0-0061566
049	0+1000118	050	0-0999958	051	0F0097123	052	0F0049823	053	0F0018863
054	0F0000003	055	0F0015903	056	0F0000353	057	0F0000003	058	0F0048513
059	0F0190153	060	0F0031743	061	0F0102783	062	0F0023833	063	0F0039463
064	0F0050503	065	0F0030813	066	0F0019403	067	0F0000003		
222	T150800	000	0-0000146	001	0-0056446	002	0-0054836	003	0-0053136
004	0-0051216	005	0-0053426	006	0-0000546	007	0-0053106	008	0-0053086
009	0-0053466	010	0-0053426	011	0-0053186	012	0-0052896	013	0-0050106
014	0-0050706	015	0-0050626	016	0-0049816	017	0-0050716	018	0+0007756
019	0-0016836	020	0-0053716	021	0-0056956	023	0-0055296	024	0-0049146
025	0-0053066	026	0-0045636	027	0-0053006	028	0-0053336	029	0-0054036
030	0-0051086	031	0-0053416	032	0-0050546	033	0-0056896	035	0-0061586
049	0+1000128	050	0-0999958	051	0F0097123	052	0F0049823	053	0F0018873
054	0F0000003	055	0F0015903	056	0F0000393	057	0F0000003	058	0F0048523
059	0F0190153	060	0F0031743	061	0F0102783	062	0F0022233	063	0F0039463
064	0F0050513	065	0F0030813	066	0F0019413	067	0F0000003		

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004 0-0040936 005 0-0039626 007 0-0043006 008 0-0042746 009 0-0043496
010 0-0043166 011 0-0040056 012 0-0039136 013 0-0047396 014 0-0047516
015 0-0047436 016 0-0046756 017 0-0041196 018 0+0005946 019 0-0023586
020 0-0052206 021 0-0058796 023 0-0053256 024 0-0027946 025 0-0053306
026 0-0043676 027 0-0041446 028 0-0042006 029 0-0046016 030 0-0047916
031 0-0043056 032 0-0045336 033 0-0053016 034 0-0057706 035 0-0061426
049 0+1000058 050 0-1000058 051 0F0097143 052 0F0050043 053 0F0018683
054 0F0082763 055 0F0016183 056 0F0000003 057 0F0044853 058 0F0048663
059 0F0188823 060 0F0000013 061 0F0103623 062 0F0055153 063 0F0037133
064 0F0048363 065 0F0029933 066 0F0017583 067 0F0000003
222   T050001  000 0+0000206 001 0-0055926 002 0-0054396 002 0-0052656
004 0-0040916 005 0-0039596 007 0-0042996 008 0-0042716 009 0-0043476
010 0-0043136 011 0-0040016 012 0-0039126 013 0-0047376 014 0-0047506
015 0-0047416 016 0-0046746 017 0-0041196 018 0+0004816 019 0-0024776
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031 0-0043016 032 0-0045346 033 0-0052996 034 0-0058046 035 0-0061406
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064 0F0048343 065 0F0029903 066 0F0017563 067 0F0000003
222   T060001  000 0+0000206 001 0-0055946 002 0-0054396 003 0-0052686
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049 0+1000068 050 0-1000068 051 0F0097083 052 0F0049993 053 0F0018643
054 0F0082743 055 0F0016173 056 0F0000003 057 0F0044843 058 0F0048663
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064 0F0048333 065 0F0029893 066 0F0017553 067 0F0000003
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026 0-0043616 027 0-0041446 028 0-0042046 029 0-0046056 030 0-0047946
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054 0F0082733 055 0F0016153 056 0F0000013 057 0F0044843 058 0F0048653
059 0F0188823 060 0F0000003 061 0F0103623 062 0F0055143 063 0F0037093
064 0F0048303 065 0F0029873 066 0F0017543 067 0F0000003
222   T080001  000 0+0000226 001 0-0055916 002 0-0054376 003 0-0052656
004 0-0040886 005 0-0039576 007 0-0042946 008 0-0042676 009 0-0043426
010 0-0043106 011 0-0039986 012 0-0039096 013 0-0047336 014 0-0047476
015 0-0047406 016 0-0046716 017 0-0041186 018 0+0006376 019 0-0023516
020 0-0051896 021 0-0058756 023 0-0053236 024 0-0027806 025 0-0053286
026 0-0043646 027 0-0041436 028 0-0041986 029 0-0045976 030 0-0047866
031 0-0042996 032 0-0045246 033 0-0053356 034 0-0058156 035 0-0061356
049 0+1000058 050 0-1000068 051 0F0097033 052 0F0049933 053 0F0018613
054 0F0082723 055 0F0016153 056 0F0000003 057 0F0044833 058 0F0048653
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064 0F0048293 065 0F0029863 066 0F0017523 067 0F0000003
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222	T090001	000	0+0000206	001	0-0055916	002	0-0054386	003	0-0052656
004	0-0040886	005	0-0039586	007	0-0042986	008	0-0042696	009	0-0043446
010	0-0043106	011	0-0039986	012	0-0039106	013	0-0047356	014	0-0047486
015	0-0047406	016	0-0046716	017	0-0041194	018	0+0006036	019	0-0023676
020	0-0052226	021	0-0058766	023	0-0053236	024	0-0027956	025	0-0053276
026	0-0043636	027	0-0041326	028	0-0041856	029	0-0045836	030	0-0047756
031	0-0042986	032	0-0045306	033	0-0053026	034	0-0058246	035	0-0061356
049	0+1000068	050	0-1000048	051	0F0096993	052	0F0049903	053	0F0018593
054	0F0082723	055	0F0016133	056	0F0000003	057	0F0044833	058	0F0048653
059	0F0188813	060	0F0000013	061	0F0103613	062	0F0055143	063	0F0037073
064	0F0048273	065	0F0029843	066	0F0017513	067	0F0000003		
222	T091557	000	0+0000176	001	0-0055926	002	0-0054376	003	0-0052656
004	0-0040876	005	0-0039556	007	0-0042956	008	0-0042676	009	0-0043446
010	0-0043096	011	0-0039996	012	0-0039086	013	0-0047326	014	0-0047476
015	0-0047406	016	0-0046716	017	0-0041186	018	0+0006566	019	0-0022316
020	0-0051756	021	0-0058746	023	0-0053216	024	0-0028006	025	0-0053276
026	0-0043626	027	0-0041426	028	0-0041986	029	0-0045976	030	0-0047846
031	0-0042966	032	0-0045256	033	0-0053636	034	0-0058226	035	0-0061356
049	0+1000068	050	0-1000058	051	0F0096993	052	0F0049893	053	0F0018583
054	0F0082713	055	0F0016143	056	0F0000003	057	0F0044833	058	0F0048643
059	0F0188813	060	0F0000003	061	0F0103623	062	0F0055143	063	0F0037073
064	0F0048273	065	0F0029843	066	0F0017513	067	0F0000003		

222	T152000	000	0-0000016	001	0-0056906	002	0-0055316	003	0-0053616
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059	0F0190143	060	0F0031723	061	0F0102713	062	0F0020273	063	0F0039453
064	0F0050513	065	0F0030773	066	0F0019413	067	0F0000003		

222	T020000	000	0+0000206	001	0-0055256	002	0-0053646	003	0-0051996
004	0-0050226	005	0-0052416	006	0+0000716	007	0-0052066	008	0-0052036
009	0-0052446	010	0-0052396	011	0-0052156	012	0-0051936	013	0-0049046
014	0-0049596	015	0-0049516	016	0-0048736	017	0-0049676	018	0+0009436
019	0-0017436	020	0-0052216	021	0-0055706	023	0-0054116	024	0-0048196
025	0-0053126	026	0-0045776	027	0-0053276	028	0-0053576	029	0-0054246
030	0-0051206	031	0-0053646	032	0-0050656	033	0-0055656	035	0-0061586
049	0+1000098	050	0-1000018	051	0F0096913	052	0F0049633	053	0F0018743
054	0F0000003	055	0F0015833	056	0F0000383	057	0F0000003	058	0F0048463
059	0F0190143	060	0F0031713	061	0F0102713	062	0F0021453	063	0F0039443
064	0F0050513	065	0F0030783	066	0F0019403	067	0F0000003		
222	T030000	000	0+0000236	001	0-0056396	002	0-0054766	003	0-0053146
004	0-0051376	005	0-0053556	006	0-0000416	007	0-0053206	008	0-0053186
009	0-0053586	010	0-0053596	011	0-0053296	012	0-0053126	013	0-0050236
014	0-0050796	015	0-0050696	016	0-0049946	017	0-0050856	018	0+0007956
019	0-0016886	020	0-0053746	021	0-0056886	023	0-0055306	024	0-0049426
025	0-0053096	026	0-0045706	027	0-0053206	028	0-0053536	029	0-0054186
030	0-0051176	031	0-0053636	032	0-0050636	033	0-0056016	035	0-0061546
049	0+1000088	050	0-1000028	051	0F0096893	052	0F0049603	053	0F0018733
054	0F0000003	055	0F0015823	056	0F0000353	057	0F0000003	058	0F0048463
059	0F0190133	060	0F0031723	061	0F0102713	062	0F0020453	063	0F0039443
064	0F0050513	065	0F0030773	066	0F0019403	067	0F0000003		
222	T040000	000	0+0000246	001	0-0055866	002	0-0054226	003	0-0052626
004	0-0050836	005	0-0053026	006	0+0000136	007	0-0052676	008	0-0052656
009	0-0053066	010	0-0052976	011	0-0052756	012	0-0052556	013	0-0049686
014	0-0050196	015	0-0050136	016	0-0049366	017	0-0050296	018	0+0008736
019	0-0016176	020	0-0053106	021	0-0056286	023	0-0054726	024	0-0048836
025	0-0053106	026	0-0045726	027	0-0053236	028	0-0053596	029	0-0054256
030	0-0051216	031	0-0053666	032	0-0050646	033	0-0055326	035	0-0061556
049	0+1000098	050	0-1000028	051	0F0096873	052	0F0049593	053	0F0018713
054	0F0000013	055	0F0015813	056	0F0000303	057	0F0000003	058	0F0048463
059	0F0190133	060	0F0031713	061	0F0102703	062	0F0020973	063	0F0039443
064	0F0050503	065	0F0030773	066	0F0019403	067	0F0000003		
222	T050000	000	0+0000266	001	0-0055276	002	0-0053636	003	0-0051996
004	0-0050246	005	0-0052406	006	0+0000786	007	0-0052076	008	0-0052046
009	0-0052446	010	0-0052376	011	0-0052156	012	0-0051946	013	0-0049226
014	0-0049586	015	0-0049506	016	0-0048746	017	0-0049666	018	0+0009296
019	0-0012626	020	0-0052366	021	0-0055666	023	0-0054096	024	0-0048226
025	0-0053116	026	0-0045696	027	0-0053196	028	0-0053536	029	0-0054156
030	0-0051166	031	0-0053656	032	0-0050656	033	0-0055606	035	0-0061516
049	0+1000088	050	0-1000028	051	0F0096863	052	0F0049573	053	0F0018703
054	0F0000003	055	0F0015813	056	0F0000253	057	0F0000003	058	0F0048463
059	0F0190123	060	0F0031713	061	0F0102703	062	0F0021863	063	0F0039443
064	0F0050513	065	0F0030783	066	0F0019403	067	0F0000003		
222	T060000	000	0+0000236	001	0-0055256	002	0-0053636	003	0-0052006
004	0-0050246	005	0-0052406	006	0+0000776	007	0-0052066	008	0-0052026
009	0-0052436	010	0-0052336	011	0-0052116	012	0-0051936	013	0-0049226
014	0-0049556	015	0-0049476	016	0-004873	0+0009296			
019	0-0017386	020	0-0052506	021	0-0055656	023	0-0054086	024	0-0048256
025	0-0053136	026	0-0045756	027	0-0053276	028	0-0053606	029	0-0054236
030	0-0051176	031	0-0053636	032	0-0050626	033	0-0055526	035	0-0061576
049	0+1000088	050	0-1000028	051	0F0096843	052	0F0049553	053	0F0018693
054	0F0000003	055	0F0015803	056	0F0000323	057	0F0000003	058	0F0048453
059	0F0190133	060	0F0031703	061	0F0102693	062	0F0021923	063	0F0039433
064	0F0050503	065	0F0030783	066	0F0019403	067	0F0000003		

222	T070000	000	0+0000256	001	0-0056366	002	0-0054726	003	0-0053096
004	0-0051366	005	0-0053516	006	0-0000326	007	0-0053166	008	0-0053146
009	0-0053536	010	0-0053436	011	0-0053226	012	0-0053056	013	0-0050386
014	0-0050676	015	0-0050606	016	0-0049866	017	0-0050756	018	0+0008136
019	0-0014366	020	0-0053626	021	0-0056736	023	0-0055196	024	0-0049356
025	0-0053136	026	0-0045776	027	0-0053256	028	0-0053606	029	0-0054266
030	0-0051216	031	0-0053756	032	0-0050656	033	0-0055576	035	0-0061496
049	0+1000098	050	0-1000028	051	0F0096813	052	0F0049533	053	0F0018683
054	0F0000003	055	0F0015803	056	0F0000463	057	0F0000003	058	0F0048443
059	0F0190123	060	0F0031703	061	0F0102693	062	0F0022523	063	0F0039433
064	0F0050513	065	0F0030773	066	0F0019403	067	0F0000003		
222	T080000	000	0+0000246	001	0-0056176	002	0-0054526	003	0-0052916
004	0-0051156	005	0-0053296	006	0-0000116	007	0-0052956	008	0-0052926
009	0-0053316	010	0-0053226	011	0-0053046	012	0-0052856	013	0-0050166
014	0-0050466	015	0-0050386	016	0-0049666	017	0-0050536	018	0+0007816
019	0-0019506	020	0-0053666	021	0-0056546	023	0-0054956	024	0-0049146
025	0-0053146	026	0-0045776	027	0-0053226	028	0-0053576	029	0-0054236
030	0-0051186	031	0-0053666	032	0-0050626	033	0-0055916	035	0-0061536
049	0+1000098	050	0-1000028	051	0F0096803	052	0F0049513	053	0F0018673
054	0F0000003	055	0F0015783	056	0F0000363	057	0F0000003	058	0F0048443
059	0F0190103	060	0F0031693	061	0F0102683	062	0F0020543	063	0F0039433
064	0F0050513	065	0F0030783	066	0F0019413	067	0F0000003		

TEST CONDITION 7

Set-Up: Both skimmers are skirted around their bases. QCM #62 was moved from its parked position into the collimator beam at 12:17 on February 4.

Thruster Pulse Rate: 23 seconds per pulse

Thruster Angular Position: See Condition 2.

222	T100000	000	0+0000086	001	0-0056266	002	0-0054146	003	0-0053566
004	0-0046556	005	0-0042746	006	0+0001736	007	0-0045146	008	0-0043556
009	0-0042796	010	0-0047426	011	0-0043556	012	0-0050136	013	0-0051356
014	0-0052236	015	0-0052086	016	0-0051406	017	0-0050816	018	0+0005876
019	0-0026826	020	0-0054006	021	0-0058386	023	0-0055626	024	0+0010306
025	0-0047346	026	0-0047296	027	0-0044886	028	0-0050026	029	0-0051536
030	0-0053106	031	0-0050036	032	0-0052346	033	0-0052366	035	0-0064796
049	0+0999978	050	0-1000058	051	0F0092103	052	0F0045523	053	0F0016043
054	0F0000003	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033503
064	0F0050190193	065	0F0030683	066	0F0019493	067	0F0030373		
222	T105940	000	0+0000026	001	0-0056306	002	0-0054186	003	0-0053606
004	0-0048496	005	0-0042766	006	0+0001676	007	0-0045176	008	0-0043606
009	0-0042826	010	0-0047496	011	0-0043606	012	0-0050196	013	0-0051426
014	0-0052286	015	0-0052156	016	0-0051476	017	0-0050886	018	0+0005776
019	0-0027216	020	0-0054026	021	0-0058406	023	0-0055666	024	0+0010206
025	0-0045846	026	0-0047256	027	0-0044876	028	0-0050026	029	0-0051526
030	0-0053126	031	0-0050056	032	0-0052376	033	0-0052396	035	0-0065076
049	0+0999988	050	0-1000048	051	0F0092053	052	0F0045493	053	0F0016013
054	0F0082733	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033513
064	0F0050193	065	0F0030693	066	0F0019503	067	0F0030373		
222	T120000	000	0-0000016	001	0-0056326	002	0-0054226	003	0-0053646
004	0-0048496	005	0-0042796	006	0+0001656	007	0-0045196	008	0-0043616
009	0-0042836	010	0-0047496	011	0-0043616	012	0-0050206	013	0-0051426
014	0-0052296	015	0-0052156	016	0-0051466	017	0-0050906	018	0+0005666
019	0-0028146	020	0-0054016	021	0-0058426	023	0-0055676	024	0+0010126
025	0-0045846	026	0-0047356	027	0-0044926	028	0-0050066	029	0-0051566
030	0-0053136	031	0-0050036	032	0-0052356	033	0-0052396	035	0-0064946
049	0+1000008	050	0-1000028	051	0F0092003	052	0F0045443	053	0F0015983
054	0F0082733	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103393	062	0F0000003	063	0F0033503
064	0F0050193	065	0F0030683	066	0F0019493	067	0F0030373		
222	T130000	000	0-0000036	001	0-0056346	002	0-0054236	003	0-0053656
004	0-0048516	005	0-0042816	006	0+0001616	007	0-0045236	008	0-0043646
009	0-0042866	010	0-0047526	011	0-0043646	012	0-0050226	013	0-0051436
014	0-0052316	015	0-0052166	016	0-0051486	017	0-0050936	018	0+0005786
019	0-0027536	020	0-0054046	021	0-0058446	023	0-0055716	024	0+0009976
025	0-0045826	026	0-0047346	027	0-0044966	028	0-0050076	029	0-0051576
030	0-0053176	031	0-0050076	032	0-0052416	033	0-0052426	035	0-0065516
049	0+0999998	050	0-1000028	051	0F0091953	052	0F0045403	053	0F0015963
054	0F0082733	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033493
064	0F0050193	065	0F0030683	066	0F0019503	067	0F0030373		
222	T134913	000	0-0000046	001	0-0056326	002	0-0054236	003	0-0053646
004	0-0046636	005	0-0042836	006	0+0001626	007	0-0045266	008	0-0043676
009	0-0042896	010	0-0047536	011	0-0043656	012	0-0050216	013	0-0051426
014	0-0052316	015	0-0052166	016	0-0051476	017	0-0050926	018	0+0006496
019	0-0027456	020	0-0054026	021	0-0058426	023	0-0055716	024	0+0009916
025	0-0047056	026	0-0047356	027	0-0044956	028	0-0050066	029	0-0051556
030	0-0053166	031	0-0050216	032	0-0052496	033	0-0052496	035	0-0065696
049	0+1000008	050	0-1000018	051	0F0091903	052	0F0045373	053	0F0015933
054	0F0000003	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103393	062	0F0000003	063	0F0033503
064	0F0050193	065	0F0030683	066	0F0019473	067	0F0030383		

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222  T140000  000 0-0000056 001 0-0056336 002 0-0054236 003 0-0053646
004 0-0048556 005 0-0042856 006 0+0001596 007 0-0045276 008 0-0043676
009 0-0042906 010 0-0047556 011 0-0043676 012 0-0050236 013 0-0051456
014 0-0052346 015 0-0052196 016 0-0051506 017 0-0050946 018 0+0007096
019 0-0026646 020 0-0054036 021 0-0058416 023 0-0055716 024 0+0009916
025 0-0045636 026 0-0047356 027 0-0044956 028 0-0050076 029 0-0051586
030 0-0053186 031 0-0050076 032 0-0052526 033 0-0052466 035 0-0065526
049 0+1000018 050 0-1000018 051 0F0091903 052 0F0045353 053 0F0015923
054 0F0082743 055 0F0015793 056 0F0000013 057 0F0000003 058 0F08723 06(
064 0F0050193 065 0F0030683 066 0F0019483 067 0F0030373
222  T141816  000 0-0000036 001 0-0056296 002 0-0054186 003 0-0053596
004 0-0048496 005 0-0042806 006+0001646 007 0-0045236 008 0-0043636
009 0-0042886 010 0-0047536 011 0-0043656 012 0-0050226 013 0-0051446
014 0-0052336 015 0-0052196 016 0-0051506 017 0-0050966 018 0+0008056
019 0-0026256 020 0-0053996 021 0-0058426 023 0-0055736 024 0+0009866
025 0-0045576 026 0-0047366 027 0-0044956 028 0-0050106 029 0-0051606
030 0-0053196 031 0-0050096 032 0-0052426 033 0-0052446 035 0-0065476
049 0+1000008 050 0-1000018 051 0F0091883 052 0F0045353 053 0F0015923
054 0F0000003 055 0F0015793 056 0F0000003 057 0F0000003 058 0F0000003
059 0F0188723 060 0F0000003 061 0F0103393 062 0F0000003 063 0F0033503
064 0F0050193 065 0F0030683 066 0F0019473 067 0F0030373
222  T150000  000 0-0000056 001 0-0056276 002 0-0054186 003 0-0053606
004 0-0048546 005 0-0042846 006 0+0001596 007 0-0045266 008 0-0043686
009 0-0042926 010 0-0047566 011 0-0043686 012 0-0050246 013 0-0051486
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019 0-0024746 020 0-0054056 021 0-0058416 023 0-0055716 02 026 0-004737
030 0-0053186 031 0-0050086 032 0-0052416 033 0-0052426 035 0-0065426
049 0+1000008 050 0-1000018 051 0F0091843 052 0F0045313 053 0F0015903
054 0F0082733 055 0F0015793 056 0F0000003 057 0F0000003 058 0F0000003
059 0F0188723 060 0F0000003 061 0F0103393 062 0F0000003 063 0F0033493
064 0F0050193 065 0F0030683 066 0F0019473 067 0F0030373
222  T160000  000 0-0000136 001 0-0056346 002 0-0054216 003 0-0053646
004 0-0046706 005 0-0042916 006 0+0001546 007 0-0045346 008 0-0043736
009 0-0042976 010 0-0047606 011 0-0043726 012 0-0050276 013 0-0051506
014 0-0052366 015 0-0052216 016 0-0051526 017 0-0050996 018 0+0006966
019 0-0026916 020 0-0054046 021 0-0058436 023 0-0055756 024 0+0009646
025 0-0046956 026 0-0047406 027 0-0045006 028 0-0050106 029 0-0051616
030 0-0053216 031 0-0050126 032 0-0052456 033 0-0052466 035 0-0065266
049 0+1000018 050 0-1000008 051 0F0091793 052 0F0045283 053 0F0015863
054 0F0000003 055 0F0015793 056 0F0000003 057 0F0000003 058 0F0000003
059 0F0188723 060 0F0000003 061 0F0103393 062 0F0000003 063 0F0033503
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222  T170000  000 0-0000156 001 0-0056326 002 0-0054206 003 0-0053636
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054 0F0000003 055 0F0015793 056 0F0000003 057 0F0000003 058 0F0000003
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064 0F0050173 065 0F0030673 066 0F0019473 067 0F0030373
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222	T180000	000	0-0000146	001	0-0056326	002	0-0054196	003	0-0053626
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009	0-0043016	010	0-0047656	011	0-0043776	012	0-0050306	013	0-0051526
014	0-0052396	015	0-0052256	016	0-0051566	017	0-0051046	018	0+0006956
019	0-0025856	020	0-0054096	021	0-0058446	023	0-0055786	024	0+0009496
025	0-0045506	026	0-0047456	027	0-0045056	028	0-0050136	029	0-0051646
030	0-0053346	031	0-0050246	032	0-0052506	033	0-0052516	035	0-0065876
049	0+1000018	050	0-1000018	051	0F0091693	052	0F0045203	053	0F0015803
054	0F0082743	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103393	062	0F0000003	063	0F0033493
064	0F0050183	065	0F0030673	066	0F0019453	067	0F0030373		
222	T190000	000	0-0000096	001	0-0056276	002	0-0054136	003	0-0053566
004	0-0048626	005	0-0042926	006	0+0001556	007	0-0045366	008	0-0043756
009	0-0042996	010	0-0047636	011	0-0043746	012	0-0050276	013	0-0051486
014	0-0052366	015	0-0052216	016	0-0051516	017	0-0050976	018	0+0007056
019	0-0026836	020	0-0054006	021	0-0058376	023	0-0055706	024	0+0009496
025	0-0045546	026	0-0047386	027	0-0045006	028	0-0050086	029	0-0051606
030	0-0053166	031	0-0050106	032	0-0052396	033	0-0052406	035	0-0065046
049	0+1000018	050	0-1000028	051	0F0091643	052	0F0045153	053	0F0015783
054	0F0082733	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033493
064	0F0050183	065	0F0030673	066	0F0019453	067	0F0030373		
222	T200000	000	0-0000076	001	0-0056236	002	0-0054086	003	0-0053526
004	0-0046696	005	0-0042926	006	0+0001626	007	0-0045346	008	0-0043746
009	0-0042996	010	0-0047626	011	0-0043736	012	0-0050266	013	0-0051476
014	0-0052356	015	0-0052206	016	0-0051516	017	0-0050966	018	0+0007046
019	0-0026286	020	0-0054006	021	0-0058356	023	0-0055696	024	0+0009436
025	0-0047076	026	0-0047396	027	0-0045006	028	0-0050096	029	0-0051616
030	0-0053156	031	0-0050106	032	0-0052386	033	0-0052416	035	0-0064646
049	0+1000008	050	0-1000038	051	0F0091603	052	0F0045113	053	0F0015753
054	0F0000003	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188723	060	0F0000003	061	0F0103393	062	0F0000003	063	0F0033483
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059	0F0188733	060	0F0000003	061	0F0103393	062	0F0000003	063	0F0033483
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059	0F0188733	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033483
064	0F0050173	065	0F0030673	066	0F0019443	067	0F0030373		
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059	0F0188733	060	0F0000003	061	0F0103393	062	0F0000003	063	0F0033483
064	0F0050173	065	0F0030663	066	0F0019443	067	0F0030373		
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059	0F0188733	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033483
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OCT 78 L C PLESS, L K RUDOLPH, D J FITZGERALD F04611-77-X-0026
UNCLASSIFIED JPL-PUB-78-96 AFRPL-TR-78-63 NL

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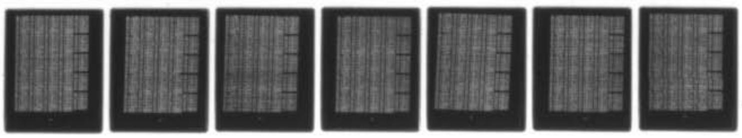

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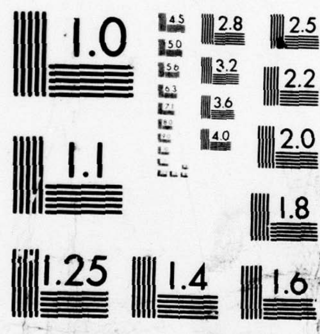

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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054	0F0082743	055	0F0015793	056	0F0000003	057	0F0000003	058	0F0000003
059	0F0188733	060	0F0000003	061	0F0103383	062	0F0000003	063	0F0033483
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064	0F0050153	065	0F0030663	066	0F0019433	067	0F0030373		
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064	0F0050153	065	0F0030673	066	0F0019433	067	0F0030363		
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054	0F0082743	055	0F0015783	056	0F0000003	057	0F0000003	058	0F0000003
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